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Low carbon economy and health in the context of carbon neutrality

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Low carbon economy and health in the context of carbon neutrality

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Editorial: Low carbon economy and health in the context of carbon neutrality

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Editorial on the Research Topic
Low carbon economy and health in the context of carbon neutrality

With climate change becoming a global concern, a low-carbon economy has become an inevitable trend. Carbon neutrality is considered an important step in curbing global greenhouse gas emissions and reducing carbon footprints. However, a low-carbon economy is not only about environmental protection but also closely related to human health. Against this background, a special topic on low-carbon economy and health in the context of carbon neutrality is proposed, aiming to promote the emergence of a series of emerging research and the sustainable development of low-carbon economy and human health. The articles included under this topic have been researched from different perspectives, introducing new research perspectives, methods, and techniques for the further development of the topic, which will have a positive impact on promoting the in-depth research and development of the topic.

The topic of low-carbon economy and health in the context of carbon neutrality has been studied multidimensionally in the articles included in this topic. In terms of the doctor-patient relationship, Zhu et al. concluded that the NSGA-II algorithm performs well in the doctor-patient bilateral matching problem, but the matching accuracy needs to be further improved. In terms of the pharmaceutical supply chain, Fu and Zhao considered the risk of pharmaceutical supply chain disruption under two modes of centralized and decentralized decision-making and constructed a combined contract model to effectively coordinate the pharmaceutical supply chain under supply disruption crises, but further research is needed in the area of stable coordination of pharmaceutical supply chain with multi-levels and multi-objects. In terms of public health expenditures, Omri et al. concluded from their study that public and private health expenditure is effective in mitigating environmental degradation on health status in Saudi Arabia, especially public health expenditure. In terms of regional green development, Wang W et al. constructed a rating model for the high-quality development of China's Yangtze River Delta Green Integration Demonstration Zone, and proposed methods and approaches to measure the construction milestones of high-quality development, which provides a reference for the evaluation study of high-quality development in other city clusters. The model suitability can be further improved by combining the actual data of city clusters in future studies. In terms of government guidance, Xu et al. observed in their study that the characteristics of local government information sources (credibility, professionalism, and attractiveness) have a significant positive effect on consumers' willingness to purchase low-carbon agricultural products, which can effectively promote the development of low-carbon agriculture. However, the study lacks quantitative research on the degree of contribution of regional brand low-carbon agricultural products to the development of low-carbon agriculture. Hu et al. offer suggestions for establishing and managing a low-carbon technology innovation system, along with insights into theoretical research on public health and high-quality development in China. Wang Q et al. examine the impact mechanism of environmental education on environmental quality in the context of low-carbon economy. Wu et al. analyze the optimal use of urban resources based on public health. Bai et al. utilize unit root tests, co-integration tests, and regression analysis to empirically investigate the associations between carbon emissions and GDP in the industry, construction, and transportation sectors. Zheng et al. provide significant practical contributions to sustainable development and the promotion of responsible population growth.

To sum up, for the special topic of low-carbon economy and health in the context of carbon neutrality, researchers have carried out relevant research in the areas of healthcare resource allocation, public health resources, urban green and low-carbon development, and the process of low carbonization of sub-fields. The further deepening of this topic expands the research field, provides subdivided research directions, relevant theoretical foundations, research methodological references, data support, and case analyses, and plays a positive role in promoting subsequent in-depth research. In more in-depth research in the future, the following can be further explored: the evaluation system of healthcare resource allocation and the construction of a low-carbon supply chain, the supply and allocation of public health resources in less developed regions, the quantitative assessment method of the impact of low-carbon economic policies and measures on health, and the process of decarbonization in the fields of agriculture, industry, and urban construction, as well as synergistic effects among different fields.

Author contributions

YZ: Writing—original draft. ZL: Writing—review and editing. CH: Writing—review and editing.

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Doctor-patient bilateral matching considering diagnosis and treatment perception in the absence of public health resources

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Introduction: The public health crisis is one of the main threats affecting the sustainable development of the economy and strengthening the rational allocation of medical resources is essential for building a strong public health system. Therefore, the study of the doctor-patient bilateral matching has important theoretical and practical significance and perception of diagnosis and treatment is taken as a key consideration in the research.

Methods: Based on the current situation of the medical industry and the main contradiction between supply and demand of medical services, an evaluation index of doctor-patient satisfaction is constructed in this paper. Then, based on the different forms of evaluation, calculate the doctor's satisfaction and patient's satisfaction respectively. Taking maximizing the overall satisfaction of doctors and patients, maximizing the number of patients and minimizing the workload difference between doctors as the decision-making objectives, considering the upper limit of doctors' working hours as the constraint condition, a multi-objective decision-making model is constructed and solved by NSGA-II algorithm to realize the matching between doctors and patients.

Conclusion: Finally, through the comparison with NSGA-III algorithm in three dimensions: the degree of convergence to the reference set, the propagation range of the solution and the running time of the algorithm, it is proved that NSGA-II algorithm has good performance in solving the matching problem of medical service supply and demand.

KEYWORDS

doctor-patient bilateral matching, diagnosis and treatment perception, public health, multi-objective decision-making, NSGA-II algorithm

1. Introduction

People's health is the most basic livelihood issue and a strong public health system provides a strong guarantee for people's health. The improvement of people's material living standards has fundamentally changed people's understanding of medical and health values (1). As a world populous country, China has 18% of the world's population, but public health resources are relatively scarce. At the same time, today's medical service is expanding to "prevention-treatment-rehabilitation-health care" based on the traditional treatment of diseases. Under the condition of limited medical resources, this will inevitably lead to the phenomenon of "medical congestion". The phenomenon of "medical congestion", that is, the limited medical resources can't meet the growing needs of patients, is essentially an imbalance between doctors and patients. In hospitals with serious "medical congestion", doctors have a greater probability of overload, which will affect the professionalism of doctors in the process of diagnosis and treatment to a certain extent.

Research shows that about 70% of urban hospitals will turn ambulances due to "medical congestion", resulting in some emergency patients missing the golden age of treatment (2). In addition, "medical congestion" is easy to prolong patients' waiting time for treatment, treatment cycle and treatment cost, resulting in low satisfaction and becoming the fuse of doctor-patient contradictions (3). Therefore, applying advanced information technology and products to the daily practice of medical management, integrating existing resources and realizing the reasonable matching between doctors and patients on the premise of ensuring the continuous increase of medical investment, has very important practical significance for improving the operation efficiency of medical work, optimizing the allocation of medical resources and promoting the development of public health (4).

Academia has applied the bilateral matching theory to many different fields. Liu et al. have applied the bilateral matching theory to the field of education to improve the perceived satisfaction of teachers and students through the matching decision between graduate freshmen and tutors, and solved the decision model with genetic algorithm (5). Wu et al. applied the bilateral matching theory to the financial field to solve the matching problem between financial products and the actual needs of enterprises from the perspective of enterprise risk bearing and financing theory (6). Jiang and Yuan applied the bilateral matching theory to the field of human resources to realize the bilateral matching between the existing post holders and external applicants by considering the fairness of competition and the stability of employees (7). Zhu et al. applied the field of bilateral matching to the field of transportation, and studied the matching between vehicle source and goods source by considering the fairness and satisfaction of matching subjects (8). Cao and Yang applied the bilateral matching theory to the communication field and studied the uplink NOMA user pairing method (9). Yu applied the bilateral matching theory to the practice of PPP projects and studied the impact of different matching mechanisms on the game results (10).

Some scholars have also applied the bilateral matching theory to the practice of medical management, but there are few studies on the matching between doctors and patients. Considering the coexistence of patients' expectation hesitation and determination in the diagnosis and treatment process, Lu et al. constructed a multi-objective function with the goal of maximizing the comprehensive satisfaction of the matching subject and minimizing the difference between patients and doctors. When solving, the multi-objective function was transformed into a single objective function for solution to realize the accurate matching of doctors and patients in the context of remote treatment (11). Wang et al. used the two-stage matching method to divide the matching between patients and doctors into two stages. Firstly, patients are divided into balanced groups according to the individual needs of patients. Then, the patient satisfaction is calculated according to the patient's expectations, and the matching between patients and doctors is realized by establishing a matching model (12). When building the decision-making model, Chen and Wang considered the hesitation and uncertainty of doctors and patients, and studied the matching between doctors and patients on the intelligent diagnosis and treatment platform by calculating the difference between the expectation and the actual situation of both sides (13). Zhong introduced the matching theory into the practical application of the medical and health industry and proposed that doctors' personalized preference plays a vital role in the stability of team work. Therefore, he considered the personalized preference of patients in the research process (14). Gao et al. considered the individual needs of patients and took maximizing doctor-patient satisfaction as the decision-making goal to realize doctor-patient bilateral matching (15). From the perspective of patients' needs, Yuan et al. considered the attention to the differences of doctors' attributes and doctors' operation types in the process of diagnosis and treatment, and studied the matching strategy taking the satisfaction and stability of doctors and patients into account (16). Ferreira et al. established a multi-objective decision-making model to match the satisfaction of both parties and maximize the utilization efficiency of medical resources, and studied the surgical resource scheduling problem (17). Neyshabouri and Berg proposed a two-stage decision-making matching method to realize the matching between patients and medical resources in consideration of the differences in the skills required by patients (18).

To sum up, the existing research provides a reference for doctor-patient bilateral matching, but there are also some deficiencies. Although the psychological perception of both matching parties is considered in literature (19), the multi-objective function is transformed into a single objective function when solving, which will lead to the complex topology of the weighted objective function and the deviation between the decision result and the actual result. Literature (12, 14) only consider the satisfaction of one of the matching subjects, which may reduce the patient's experience and the doctor's work efficiency. Literature (13, 15, 16) consider the satisfaction of doctors and patients, but does not take the measurement of workload among doctors into account, which may lead to overload of some doctors. Therefore, this paper takes maximizing the overall satisfaction of doctors and patients, maximizing the number of patients and minimizing the workload difference between doctors as the decision-making objectives, considers the upper limit of doctors' working hours as the constraint, constructs a multi-objective decision-making model, and proposes a matching method that fully considers the actual demands of doctors and patients in the diagnosis and treatment process.

2. Problem description and symbol description

2.1. Problem description

The essence of doctor-patient bilateral matching decision is to form the doctor-patient matching result with the highest comprehensive utility by using technical means or management methods based on certain decision-making objectives. When patients receive medical services, they have psychological expectations for the doctors who provide medical services to themselves, usually including professional technology, moral cultivation, charging standard and so on. When patients register on the reservation platform, they can express their needs on the platform and form a patient expectation matrix. Similarly, doctors also have psychological expectations for the objects they provide medical services, mainly including the expectations of patients' disease types and patients' quality. Doctors can submit their preferences to hospital management decision-makers to form a doctor expectation matrix.

At the same time, hospital management decision-makers need to objectively evaluate doctors and patients based on the same dimension to calculate doctors' satisfaction and patients' satisfaction. In the decision-making process, the decision-makers aim to meet the expectations of both doctors and patients as much as possible, take the number of patients and doctors' workload into account, and comprehensively weigh among various factors to form a matching pair with the highest comprehensive utility. The hierarchical structure of doctor-patient bilateral matching decision is shown in Figure 1.

2.2. Symbol description

$(D_1, D_2, \ldots, D_n)$: Collection of patients, where D_i represents patient i, $i = 1, 2, \ldots, n$.

$(S_1, S_2, \ldots, S_k)$: Collection of doctors, where S_m represents patient m, $m = 1, 2, \ldots, k$.

$(C_1, C_2, \ldots, C_h)$: The collection of attributes of the patient's evaluation index to the doctor, where C_l represents attribute l, $l = 1, 2, \ldots, h$. Matching attributes have three forms: clarity number, interval number and language evaluation.

$(Q_1, Q_2, \ldots, Q_j)$: The collection of the attributes of the doctor's evaluation indicators for patients, where Q_υ represents attribute υ, $\upsilon = 1, 2, \ldots, j$. The form of matching attribute is the same as above.

$E = [e_{il}]_{n\times h}$: The expectation matrix of the patient to the doctor, where e_{ig} represents the expectation level of the patient D_i about the attribute C_l of the medical service, $i = 1, 2, \ldots, n$, $l = 1, 2, \ldots, h$.

$F = [e_{m\alpha}]_{k\times j}$: The expectation matrix of the doctor to the patient, where $e_{m\alpha}$ represents the expectation level of the doctor S_m about the attribute Q_α of the medical service, $m = 1, 2, \ldots, k$, $\alpha = 1, 2, \ldots, j$.

$A = [a_{ml}]_{k\times h}$: The evaluation matrix of the decision-maker to the doctor, where a_{ml} represents the evaluation level of the decision-maker on the attribute C_l of doctor S_m, $m = 1, 2, \ldots, k$, $l = 1, 2, \ldots, h$.

$B = [a_{i\alpha}]_{n\times j}$: The evaluation matrix of the decision-maker to the patient, where $a_{i\alpha}$ represents the evaluation level of the decision-maker on the attribute Q_α of patient D_i, $i = 1, 2, \ldots, n$, $\alpha = 1, 2, \ldots, j$.

p_i: Severity of patient D_i. It is divided into five levels of 1–5, of which the larger the number, the more serious the patient's condition is.

t_i: Estimated treatment time of patient D_i.

T: The maximum working hours per doctor per day.

3. Model construction of doctor-patient bilateral matching decision

3.1. Construction of evaluation index system for doctor satisfaction and patient satisfaction

Based on the current main contradiction between supply and demand of medical services, the evaluation index system of doctor-patient satisfaction is constructed. The construction process of the index system follows the principles of professionalism, comprehensiveness and timeliness. Professionalism: Research on the evaluation index system of academic doctor-patient satisfaction, combined with the visit and investigation of front-line medical workers, to ensure the professionalism of the index system from two aspects of professional theory and reality; Comprehensiveness: fully consider patients' expectations on doctors' professional skills, moral cultivation, charging standards, and doctors' expectations on patients' condition and quality, and ensure that the evaluation indicators fully reflect the psychological feelings of the matching subjects in the diagnosis and treatment process; Timeliness: considering the characteristics of the times of the medical industry, for example, today's medicine has changed from a simple biomedical model to a combination of "biomedicine + social psychology", so social psychological factors should be fully considered when constructing indicators.

Therefore, patients comprehensively evaluate whether doctors meet their expectations from five aspects professional level (C_1), service attitude (C_2), reputation (C_3), humanistic concerns (C_4), and fees (C_5). At the same time, doctors' preferences for patients are mainly considered from the four dimensions of resource urgency (Q_1), expertise similarity (Q_2), cooperation (Q_3), and patience (Q_4). Among them, cost indicators include fees (C_5) and resource urgency (Q_1), and the rest are benefit indicators.

3.2. Calculate patient satisfaction

Patients put forward their expectations for doctors from different dimensions and decision-makers evaluate doctors from the same dimension, and then consider whether the actual situation of doctors meets the needs of patients. Therefore, to measure this satisfaction, it is necessary to calculate the patient satisfaction based on the patient's expectation matrix and the doctor's evaluation matrix. Patients' evaluation of doctors mainly includes clarity number, interval number and language evaluation. Specifically, the satisfaction calculation formula of the three evaluation forms is as follows.

3.2.1. Patient satisfaction when the evaluation type is clear number

Suppose that the patient's expectation level for the doctor is $e_{il} = e_{il}'$, and the decision-maker's evaluation level for the doctor is $a_{ml} = a_{ml}'$, where $e_{il}' \geq 0$, $a_{ml}' \geq 0$. At this time, for attribute C_l, the satisfaction u_{im}^l of patient D_i to doctor S_m is calculated as follows:

When the index is a benefit index:

$$u_{im}^l = \begin{cases} \frac{e_{il}' - a_{ml}'}{e_{il}'}, e_{il}' > a_{ml}'; \\ 1, e_{il}' \leq a_{ml}'. \end{cases} \quad i = 1, 2, ..., n, m = 1, 2, ..., k, l = 1, 2, ..., h \tag{1}$$

When the indicator is a cost indicator:

$$u_{im}^l = \begin{cases} 1, e_{il}' \geq a_{ml}'; \\ \frac{a_{ml}' - e_{il}'}{e_{il}'}, e_{il}' < a_{ml}'. \end{cases} \quad i = 1, 2, ..., n, \; m = 1, 2, ..., k, \; l = 1, 2, ..., h \tag{2}$$

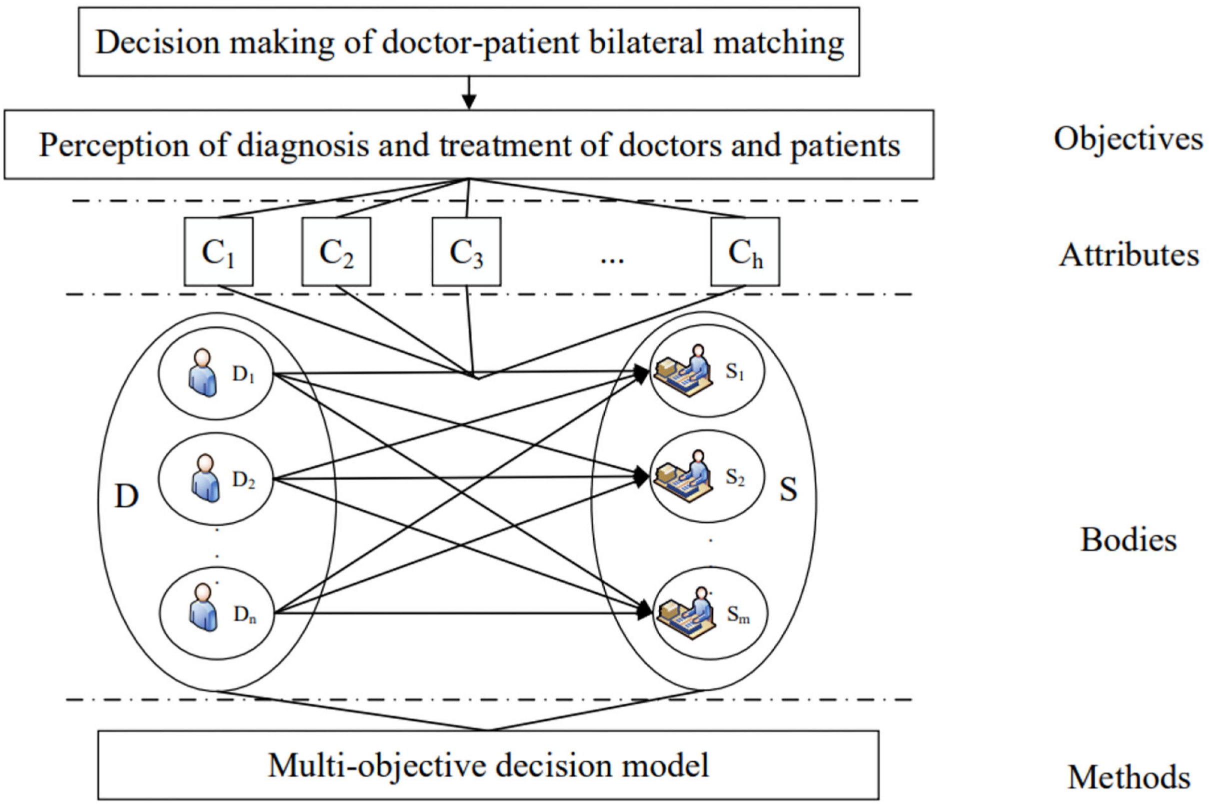

FIGURE 1
The hierarchical structure of doctor-patient bilateral matching decision.

Where benefit indicators are positive indicators (i.e., the larger the better), and cost indicators are negative indicators (i.e., the smaller the better).

3.2.2. Patient satisfaction when the evaluation type is interval number

Suppose that the patient's expectation level for the doctor is $e_{il} = \left[e_{il}^{L}, e_{il}^{R}\right]$, and the decision-maker's evaluation level for the doctor is a_{ml}, where $e_{il}^{R} \geq e_{il}^{L} \geq 0$. At this time, for attribute C_l, the satisfaction u_{im}^{l} of patient D_i to doctor S_m is calculated as follows:

$$u_{im}^{l} = \begin{cases} \frac{e_{il}^{L}-a_{ml}}{e_{il}^{L}}, a_{ml} < e_{il}^{L}; \\ 1, e_{il}^{L} \leq a_{ml} \leq e_{il}^{R}; \\ \frac{a_{ml}-e_{il}^{R}}{e_{il}^{R}}, a_{ml} > e_{il}^{R}. \end{cases} \quad i = 1, 2, ..., n, \ m = 1, 2, ..., k, \ l = 1, 2, ..., h \tag{3}$$

3.2.3. Patient satisfaction when the evaluation type is short sentences

Suppose that the patient's short sentence evaluation of the doctor is represented by $O = \left\{O_1, ..., O_g\right\}$, where O_c represents the short sentence c in set O, and g is the granularity of set O. Suppose that the granularity level of the patient's expectation level e_{il} of the doctor is expressed as δ_{il} (e.g., when the patient's evaluation of the doctor is O_3, $\delta_{il} = 3$), and the granularity level of the decision-maker's evaluation level a_{ml} of the doctor is expressed as β_{ml}. At this time, for attribute C_l, the satisfaction u_{im}^{l} of patient D_i to doctor S_m is calculated as follows:

When the index is a benefit index:

$$u_{im}^{l} = \begin{cases} \frac{\delta_{il}-\beta_{ml}}{\delta_{il}}, \delta_{il} > \beta_{ml}; \\ 1, \delta_{il} \leq \beta_{ml}. \end{cases} \quad i = 1, 2, ..., n, m = 1, 2, ..., k, \ l = 1, 2, ..., h \tag{4}$$

When the indicator is a cost indicator:

$$u_{im}^{l} = \begin{cases} 1, \delta_{il} \geq \beta_{ml}; \\ \frac{\beta_{ml}-\delta_{il}}{\beta_{ml}}, \delta_{il} < \beta_{ml}. \end{cases} \quad i = 1, 2, ..., n, \ m = 1, 2, ..., k, \ l = 1, 2, ..., h \tag{5}$$

Based on the above different types of evaluation forms, calculate patient satisfaction u_{im}^{l}. Combined with weight w_l, the comprehensive satisfaction of patient D_i to doctor S_m is:

$$U_{im} = \sum_{l=1}^{h} w_l u_{im}^{l} \tag{6}$$

3.3. Calculate doctor satisfaction

Like patients, doctors also have psychological expectations for patients in the process of diagnosis and treatment. Based on the

TABLE 1 Characteristic information of patients.

Patient number	Age	Sex	Illness degree	Estimated time of diagnosis (h)	Patient number	Age	Sex	Illness degree	Estimated time of diagnosis (h)
D_1	31	M	2	1.5	D_{10}	46	M	3	2.5
D_2	37	M	3	2	D_{11}	39	M	4	1.5
D_3	48	F	2	1.5	D_{12}	33	F	5	3
D_4	21	F	2	1	D_{13}	34	M	2	1.5
D_5	26	M	4	2	D_{14}	33	M	3	2
D_6	23	F	1	0.5	D_{15}	20	F	4	2.5
D_7	18	F	3	2	D_{16}	54	M	3	2
D_8	29	M	4	2.5	D_{17}	52	F	2	1
D_9	53	F	2	0.5	D_{18}	47	M	2	1

expectation matrix of doctors for patients, decision-makers evaluate patients from the same dimension, and then consider whether the actual situation of patients meets the needs of doctors.

3.3.1. Doctor satisfaction when the evaluation type is clear number

Suppose that the doctor's expectation level for the patient is $e_{m\upsilon} = e_{m\upsilon}{}'$, and the decision-maker's evaluation level for the patient is $a_{i\upsilon} = a_{i\upsilon}{}'$, where $e_{m\upsilon}{}' \geq 0$, $a_{i\upsilon}{}' \geq 0$. At this time, for attribute Q_υ, the satisfaction u^{υ}_{mi} of doctor S_m to patient D_i is calculated as follows:

$$u^{\upsilon}_{mi} = \begin{cases} \frac{e_{m\upsilon}{}' - a_{i\upsilon}{}'}{e_{m\upsilon}{}'},\ e_{m\upsilon}{}' > a_{i\upsilon}{}'; \\ 1\ ,\ e_{m\upsilon}{}' \leq a_{i\upsilon}{}'. \end{cases} \quad i = 1, 2, ..., n,\ \ m = 1, 2, ..., k, \quad \upsilon = 1,\ 2, \ldots, j \tag{7}$$

3.3.2. Doctor satisfaction when the evaluation type is short sentences

The doctor's short sentences evaluation of the patient can refer to the form of the patient's short sentences of the doctor, expressed as $O = \{O_1, ..., O_g\}$, where O_c represents the short sentence c in set O, and g is the granularity of set O. Suppose that the granularity level of the doctor's expectation level $e_{m\upsilon}$ of the patient is expressed as $\gamma_{m\upsilon}$, and the granularity level of the decision-maker's evaluation level $a_{i\upsilon}$ of the doctor is expressed as $\eta_{i\upsilon}$. At this time, for attribute Q_υ, the satisfaction u^{υ}_{mi} of doctor S_m to patient D_i is calculated as follows:

$$u^{\upsilon}_{mi} = \begin{cases} \frac{\eta_{i\upsilon} - \gamma_{m\upsilon}}{\eta_{i\upsilon}},\ \eta_{i\upsilon} > \gamma_{m\upsilon}; \\ 1\ ,\ \gamma_{m\upsilon} \leq \eta_{i\upsilon}. \end{cases} \quad i = 1, 2, ..., n, m = 1, 2, .., k, \upsilon = 1,\ 2, ..j \tag{8}$$

Based on the above different types of evaluation forms, calculate doctor satisfaction u^{υ}_{im}. Combined with weight w_χ, the comprehensive satisfaction of doctor S_m to patient D_i is:

$$\bar{U}_{mi} = \sum_{\upsilon=1}^{j} w_\chi u^{\upsilon}_{mi} \tag{9}$$

3.4. Construction of multi-objective decision model

Suppose that the matching variable x_{im} between the doctor and the patient follows the 0–1 integer programming, that is, when the matching between patient D_i and doctor S_m is successful, $x_{im} = 1$; Conversely, if there is no match, $x_{im} = 0$.

In the process of establishing the decision-making model, while meeting the basic diagnosis and treatment needs of patients, further consider the negative impact of the workload on doctors and diagnosis and treatment results, and measure it from the following three factors:

Factor 1: The difference in the number of patients received by each doctor should be as small as possible.

$$\min \sum_{m=1}^{q-1} \sum_{r>m}^{q} \left| \sum_{i=1}^{n} x_{im} - \sum_{i=1}^{n} x_{ir} \right| \tag{10}$$

Factor 2: Each doctor should accept the number of patients with the same severity as possible.

$$\min \sum_{m=1}^{q-1} \sum_{r>m}^{q} \left| \sum_{i=1}^{n} p_i x_{im} - \sum_{i=1}^{n} p_i x_{ir} \right| \tag{11}$$

Factor 3: The difference in the working hours of each doctor every day should be as small as possible.

$$\min \sum_{m=1}^{q-1} \sum_{r>k}^{q} \left| \sum_{i=1}^{n} t_i x_{im} - \sum_{i=1}^{n} t_i x_{ir} \right| \tag{12}$$

Suppose v_1, v_2 and v_3 are the weight of three factors that balance the workload between doctors. A multi-objective decision-making model for doctor-patient bilateral matching is constructed based on three factors: satisfaction, number of patients and doctor workload.

$$\begin{cases} \max Z_1 = \sum\limits_{i=1}^{n}\sum\limits_{m=1}^{k} U_{im}x_{im} + \sum\limits_{i=1}^{n}\sum\limits_{m=1}^{k} \bar{U}_{mi}x_{im} \\ \max Z_2 = \sum\limits_{i=1}^{n}\sum\limits_{m=1}^{k} x_{im} \\ \min Z_3 = v_1 \sum\limits_{m=1}^{q-1}\sum\limits_{r>m}^{q} \left| \sum\limits_{i=1}^{n} x_{im} - \sum\limits_{i=1}^{n} x_{ir} \right| \\ +v_2 \sum\limits_{m=1}^{q-1}\sum\limits_{r>m}^{q} \left| \sum\limits_{i=1}^{n} p_i x_{im} - \sum\limits_{i=1}^{n} p_i x_{ir} \right| \\ +v_3 \sum\limits_{m=1}^{q-1}\sum\limits_{r>k}^{q} \left| \sum\limits_{i=1}^{n} t_i x_{im} - \sum\limits_{i=1}^{n} t_i x_{ir} \right| \\ s.t. \sum\limits_{m=1}^{k} x_{im} \le 1 \\ s.t. \sum\limits_{i=1}^{n} t_i x_{im} \le T \end{cases} \quad (13)$$

Where $\max Z_1$ means to maximize the comprehensive satisfaction of doctors and patients in the decision-making process; $\max Z_2$ means to maximize the number of patients who can receive treatment; $\max Z_3$ means to make a decision to balance the workload among doctors as much as possible; $\sum\limits_{m=1}^{k} x_{im} \le 1$ means that each patient can only be matched with one doctor at most; $\sum\limits_{i=1}^{n} t_i x_{im} \le T$ represents the maximum working hours of each doctor in a single day.

4. Solution method of doctor-patient bilateral matching decision model

Due to the slow speed of NSGA algorithm in solving large-scale problems, as well as the restriction of objective conditions such as manually specifying the sharing radius and no elite selection strategy, it cannot reflect the good performance of the solution. Based on this, Srinivas et al. improved NSGA algorithm and proposed NSGA-II algorithm. NSGA-II algorithm further reduces the computational complexity and improves the performance in solving multi-objective decision-making problems through three steps of fast non-dominated sorting, crowding comparison operator and elite retention strategy, on the basis of ensuring population diversity (19).

The main process steps of NSGA-II algorithm are as follows:

Step 1: Generate the initial population with population size of N, denoted as P_n, and the evolution algebra of initialization population $n = 0$;

Step 2: The initial population P_n is sorted into different levels according to the difference of dominance degree, and the crowding distance of each individual is calculated at the same time;

Step 3: Select, cross and mutate the parent population to form the child population Q_n, and combine the child population with the parent population to form a new population set, which is recorded as P_{2N}.

Step 4: For the new population set P_{2N}, the elite retention strategy is adopted to retain individuals with high degree of non-domination and large crowding distance to form a new generation of population P_{n+1}.

TABLE 2 Patients' expectations of doctors.

	C_1	C_2	C_3	C_4	C_5		C_1	C_2	C_3	C_4	C_5
D_1	9	O_4	O_3	O_3	[80, 100]	D_{10}	9	O_3	O_3	O_3	[80, 120]
D_2	9	O_4	O_5	O_4	[75, 120]	D_{11}	8	O_3	O_4	O_4	[80, 100]
D_3	8	O_3	O_4	O_2	[60, 90]	D_{12}	9	O_4	O_3	O_3	[80, 100]
D_4	10	O_5	O_3	O_4	[70, 100]	D_{13}	7	O_5	O_4	O_3	[65, 95]
D_5	8	O_4	O_3	O_3	[90, 140]	D_{14}	9	O_3	O_3	O_4	[60, 80]
D_6	7	O_3	O_3	O_3	[50, 90]	D_{15}	9	O_4	O_3	O_5	[70, 105]
D_7	8	O_3	O_3	O_2	[70, 105]	D_{16}	9	O_4	O_4	O_4	[75, 115]
D_8	10	O_5	O_4	O_4	[95, 140]	D_{17}	8	O_5	O_4	O_4	[60, 75]
D_9	8	O_4	O_3	O_3	[65, 100]	D_{18}	7	O_4	O_4	O_3	[55, 80]

TABLE 3 Assessment level of doctors.

	C_1	C_2	C_3	C_4	C_5
S_1	7	O_5	O_3	O_4	72
S_2	8	O_4	O_3	O_4	78
S_3	9	O_3	O_3	O_3	90
S_4	10	O_4	O_5	O_4	110
S_5	9	O_3	O_4	O_3	88

Step 5: Repeat steps 2–4 until the population evolution algebra is greater than the set population evolution algebra.

5. Analog simulation

In order to make full use of medical resources and improve operation efficiency, the decision-makers of oral hospital hope to form a good match between doctors and patients through the reform of management system, so as to balance the workload between doctors while improving the psychological feelings of patients and doctors in the process of diagnosis and treatment.

5.1. Bilateral matching decision of doctor-patient based on NSGA-II algorithm

There were 18 patients with dental pulp disease, which was denoted as set $D = \{D_1, D_2, D_3, ..., D_{18}\}$, and the patient's characteristic information is shown in Table 1.

There are five doctors in oral hospital who treat dental pulp diseases, and the collection of doctors is $S = \{S_1, S_2, ..., S_5\}$. The expectations of patients for dentist are shown in Table 2.

Among the five evaluation dimensions, C_1 is the evaluation dimension in the form of clear number, expressed as an integer between 0 and 10, of which 10 points represent the most satisfied and 0 points represent the least satisfied; C_2, C_3 and C_4 are the evaluation dimensions expressed in the form of language short sentences, which are divided into five levels according to the degree of evaluation, namely $O = \{O_1 = \text{very poor}, O_2 = \text{poor}, O_3 = \text{medium}, O_4 = \text{good}, O_5 = \text{very good}\}$; C_5 is the evaluation dimension expressed in the form of interval number, which means that the satisfaction of patients in this interval is maximized. Based on these five evaluation dimensions, patients put forward their expectations for doctors and get the expectation matrix of patients, as shown in Table 2. At the same time, hospital decision-makers will also objectively evaluate doctors based on these five evaluation dimensions and the evaluation level of doctors is shown in Table 3.

In the doctor's evaluation dimension of patients, Q_1 and Q_2 are the evaluation dimensions in the form of clear numbers, Q_3 and Q_4 are the evaluation dimensions in the form of short sentences. Based on these four evaluation dimensions, doctors put forward their expectations for patients and get the doctor's expectation matrix, as shown in Table 4. At the same time, hospital decision-makers will also objectively evaluate patients based on these four evaluation dimensions and the evaluation level of patients is shown in Table 5.

In the decision-making process, the influence of doctors' working hours on diagnosis and treatment focus and treatment effect is fully considered, so each dentist is set to work no more than 10 h a day, that is, $T = 10$. Doctor satisfaction and patient satisfaction can be calculated through Formula (1)–(9), and a target model based on doctor-patient satisfaction can be constructed. At the same time, considering the maximization of patient reception and the minimization of workload difference between doctors, the weights of the three decision objectives are determined as $\nu_1 = 0.35$, $\nu_2 = 0.28$, and $\nu_3 = 0.37$, respectively, by Delphi method, based on which the doctor-patient bilateral matching decision model is constructed. NSGA-II algorithm is used to solve the model, and the population size $n = 200$, genetic algebra $gen = 200$, crossover probability $pc = 0.95$, mutation probability $pm = 0.05$ are set. The Pareto optimal solution is shown in Table 6, and the feasible solution is shown in Figure 2. The red triangle constitutes the solution plane satisfying the Pareto optimal condition.

TABLE 4 Doctors' expectations for patients.

	Q_1	Q_2	Q_3	Q_4
S_1	8	9	O_3	O_4
S_2	7	8	O_3	O_4
S_3	9	9	O_4	O_3
S_4	9	7	O_5	O_5
S_5	9	8	O_4	O_4

5.2. Analysis of comparison results between NSGA-II algorithm and NSGA-III algorithm

5.2.1. Comparative experimental method

To further verify the good performance of NSGA-II algorithm in solving large-scale problems, NSGA-II algorithm is compared with NSGA-III algorithm from three dimensions: convergence of algorithm solution, stability of solution distribution and algorithm running time:

(1) Convergence of solution τ. Firstly, the non inferior solutions obtained by NSGA-II algorithm and NSGA-III algorithm are combined to form a new solution set. Then calculate the average Euclidean distance from each feasible solution of the two algorithms to the nearest feasible solution in the new solution set. The formula can be expressed as:

$$\tau = (\sum_{i=1}^{N} d_i)/N \tag{14}$$

TABLE 5 Hospital evaluation level of patients.

Patients	Q_1	Q_2	Q_3	Q_4	Patients	Q_1	Q_2	Q_3	Q_4
D_1	8	9	O_5	O_5	D_{10}	9	8	O_3	O_3
D_2	9	8	O_5	O_3	D_{11}	8	8	O_5	O_4
D_3	8	9	O_4	O_2	D_{12}	10	10	O_5	O_4
D_4	7	8	O_4	O_4	D_{13}	7	9	O_4	O_3
D_5	8	10	O_3	O_3	D_{14}	8	8	O_3	O_3
D_6	7	8	O_4	O_3	D_{15}	9	9	O_4	O_5
D_7	8	9	O_3	O_2	D_{16}	7	7	O_4	O_4
D_8	10	10	O_4	O_5	D_{17}	7	8	O_5	O_4
D_9	6	7	O_3	O_3	D_{18}	7	8	O_4	O_3

TABLE 6 Pareto optimal solutions.

	Pareto optimal solution (target space) $X = (x_{1,1}, x_{1,2}, x_{1,3}, x_{1,4}, x_{1,5}, \ldots\ldots, x_{18,1}, x_{18,2}, x_{18,3}, x_{18,4}, x_{18,5})^T$	Optimal value		
		Z_1	Z_2	Z_3
1	$x_{1,3} = 1, x_{2,2} = 1, x_{3,1} = 1, x_{4,5} = 1, x_{6,3} = 1,$ $x_{7,1} = 1, x_{8,1} = 1, x_{9,4} = 1, x_{10,2} = 1, x_{11,5} = 1,$ $x_{13,1} = 1, x_{14,1} = 1, x_{16,4} = 1, x_{17,2} = 1, x_{18,3} = 1.$	27.8	15	24.8
2	$x_{1,3} = 1, x_{2,1} = 1, x_{3,1} = 1, x_{4,5} = 1, x_{6,3} = 1,$ $x_{7,1} = 1, x_{9,4} = 1, x_{10,2} = 1, x_{11,5} = 1, x_{13,1} = 1,$ $x_{14,2} = 1, x_{15,1} = 1, x_{16,4} = 1, x_{17,2} = 1, x_{18,3} = 1.$	27.8	15	27.0
3	$x_{1,3} = 1, x_{4,5} = 1, x_{5,1} = 1, x_{6,3} = 1, x_{7,1} = 1,$ $x_{8,1} = 1, x_{9,2} = 1, x_{10,2} = 1, x_{11,5} = 1, x_{12,4} = 1,$ $x_{13,1} = 1, x_{14,2} = 1, x_{15,1} = 1, x_{17,2} = 1, x_{18,3} = 1.$	28.3	15	34.7
4	$x_{1,3} = 1, x_{2,1} = 1, x_{3,1} = 1, x_{4,5} = 1, x_{5,1} = 1,$ $x_{6,3} = 1, x_{8,1} = 1, x_{9,4} = 1, x_{10,2} = 1, x_{11,5} = 1,$ $x_{13,1} = 1, x_{14,2} = 1, x_{16,4} = 1, x_{17,2} = 1, x_{18,3} = 1.$	27.8	15	25.1
5	$x_{1,3} = 1, x_{3,1} = 1, x_{4,5} = 1, x_{5,1} = 1, x_{6,3} = 1,$ $x_{7,1} = 1, x_{8,1} = 1, x_{9,2} = 1, x_{10,2} = 1, x_{11,5} = 1,$ $x_{12,4} = 1, x_{13,1} = 1, x_{14,2} = 1, x_{17,2} = 1, x_{18,3} = 1.$	28.2	15	31.0
6	$x_{1,3} = 1, x_{3,1} = 1, x_{4,5} = 1, x_{5,1} = 1, x_{6,3} = 1,$ $x_{8,1} = 1, x_{9,2} = 1, x_{10,2} = 1, x_{11,5} = 1, x_{12,4} = 1,$ $x_{13,1} = 1, x_{14,2} = 1, x_{15,1} = 1, x_{17,2} = 1, x_{18,3} = 1.$	28.2	15	32.8

Where d_i represents the average Euclidean distance between the feasible solution i and the nearest feasible solution in the new solution set, and N represents the total number of feasible solutions. The smaller the value of τ, the higher the degree of convergence of the solution.

(2) Stability of solution distribution ϖ. Firstly, the boundary solution of the feasible solution is determined, and then the Euclidean distance from the extreme solution to the boundary solution is calculated. The calculation formula can be expressed as:

$$\varpi = \frac{d_1 + d_2 + \sum_{i-1}^{N-1} |d_i - \bar{d}\,|}{d_1 + d_2 + (N-1)\bar{d}} \tag{15}$$

Where d_1 and d_2 represent the Euclidean distance between the extreme solution and the boundary solution of the feasible solution, and $\bar{d}$ represents the average Euclidean distance. The smaller the value of ϖ, the better the stability of the solution distribution.

(3) Running time t. Record the running time of the single solution model of the algorithm.

The steps of the comparative experiment are as follows:

Step 1: Patient satisfaction matrix $M_1 = (u_{ik})_{n\times m}$ and doctor satisfaction matrix $M_2 = (u_{ki})_{n\times m}$ are randomly generated, respectively, where satisfaction follows the random distribution of [0,1].

Step 2: The patient's condition degree vector $\kappa = (\kappa_1, \kappa_2, \ldots, \kappa_n)$ and the patient's estimated diagnosis and treatment time vector $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$ are randomly generated, in which the value of κ is randomly taken from set {1, 2, 3, 4, 5} and the value of λ is randomly taken from set {0.5, 1, 1.5, 2, 2.5, 3}. Based on this, the multi-objective decision-making model is constructed.

Step 3: The model is solved by NSGA-II algorithm and NSGA-III algorithm to obtain the running time of the algorithm. At the same time, the Pareto optimal solution sets W_1 and W_2 are obtained, respectively, and the set $W = W_1 \bigcup W_2$.

Step 4: Calculate the values of τ and ϖ by Formulas (14) and (15).

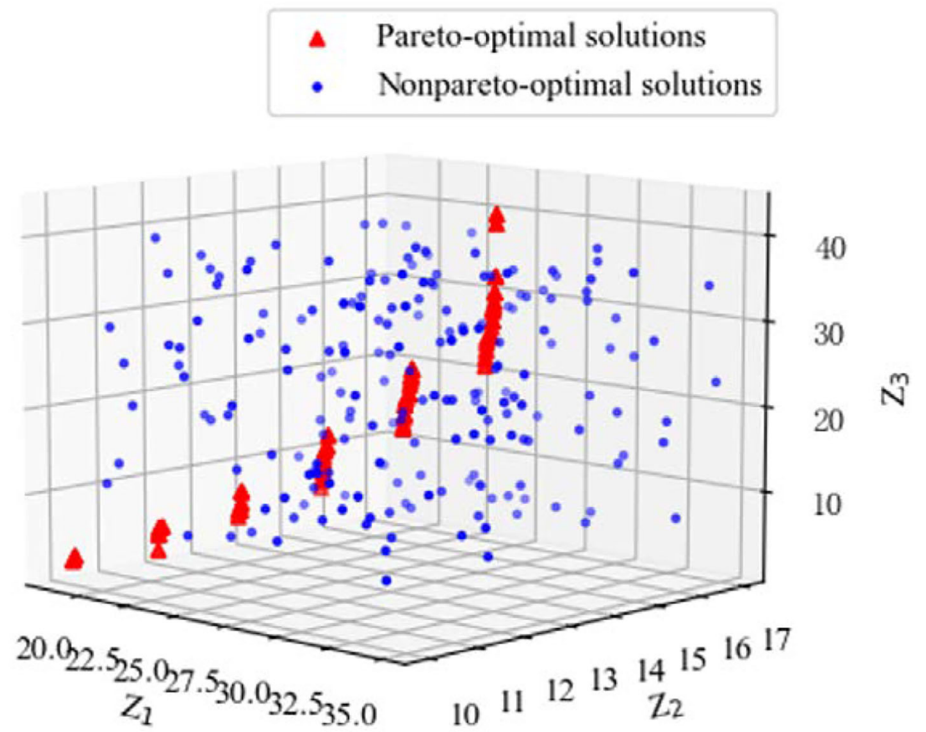

FIGURE 2
Feasible solution of doctor-patient bilateral matching decision model.

TABLE 7 Algorithm test sample.

	n	m	N	Maximum genetic algebra	p_c	p_m	Solution space Ω
1	20	5	100	100	0.95	0.05	$O(20^5)$
2	30	7	100	100	0.95	0.05	$O(30^7)$
3	40	9	150	100	0.95	0.05	$O(40^9)$
4	50	10	200	100	0.95	0.05	$O(50^{10})$
5	60	12	200	100	0.95	0.05	$O(60^{12})$
6	70	15	200	100	0.95	0.05	$O(70^{15})$
7	80	18	300	200	0.95	0.05	$O(80^{18})$
8	100	20	300	200	0.95	0.05	$O(100^{20})$
9	110	22	300	200	0.95	0.05	$O(110^{22})$
10	120	25	500	200	0.95	0.05	$O(120^{25})$
11	130	28	500	200	0.95	0.05	$O(130^{28})$
12	140	30	500	200	0.95	0.05	$O(140^{30})$

5.2.2. Comparative analysis of algorithms

By setting the number of patients n, the number of doctors m and the population size N, the problems of different sizes are constructed. For different situations, NSGA-II algorithm and NSGA-III algorithm are used to solve them for 10 times, respectively, and the average value and variance of τ and ϖ are calculated. The test sample parameters of the algorithm are shown in Table 7.

It can be seen from Figure 3 that from the two dimensions of solution convergence and stability of distribution, NSGA-II algorithm is generally smaller than NSGA-III algorithm in terms of mean and variance, which shows that NSGA-II algorithm is easier to produce non-inferior solutions close to the reference set and the generated non-inferior solutions have a more stable distribution. Therefore, compared with NSGA-III algorithm, NSGA-II algorithm has better convergence in solving large-scale problems, and the resulting non-inferior solutions have a more stable distribution. When solving large-scale problems, the running time of NSGA-II algorithm and NSGA-III algorithm in all test problems is very close,

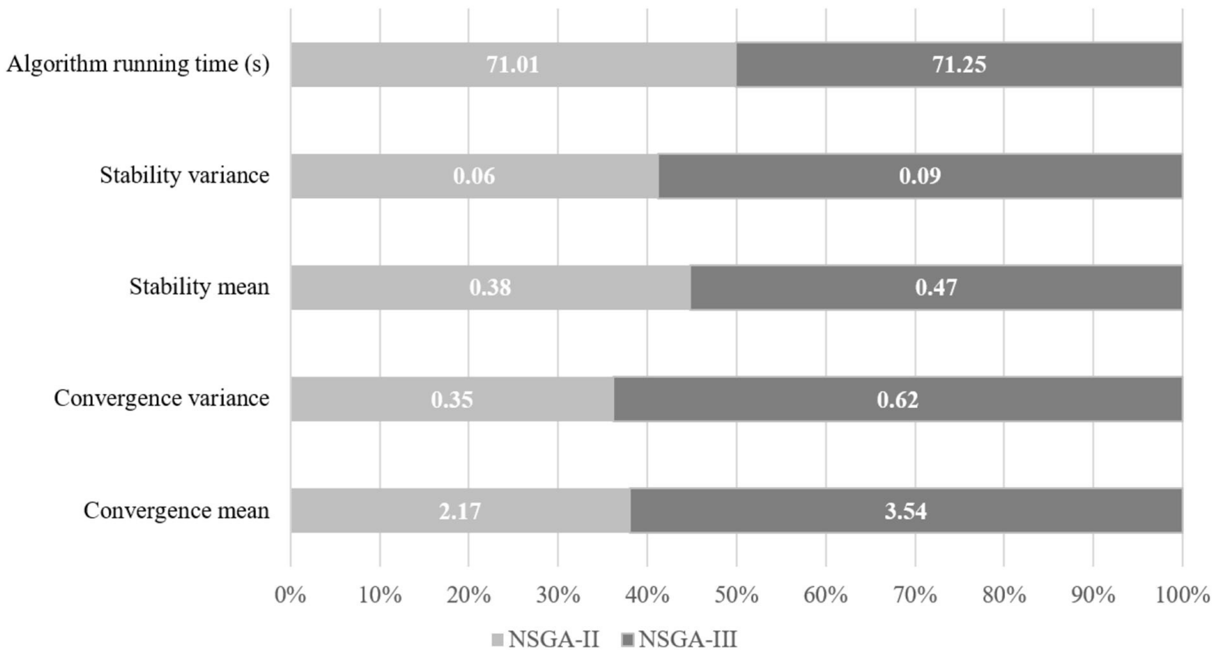

FIGURE 3
Performance comparison of NSGA-II and NSGA-III algorithms.

but the solution speed of NSGA-II algorithm is faster on the whole. It shows that NSGA-II algorithm produces non-inferior solutions faster in general.

Therefore, it can be concluded that NSGA-II algorithm has better performance in solving the problem of bilateral matching of doctor-patient.

6. Summary and prospect

The rational allocation of medical resources plays an important role in building a sound public health system. The outbreak of the COVID-19 epidemic has exposed the inadequacy of current public health planning. Studying how to realize the rational allocation of medical resources plays an important role in promoting the sustainable, stable and development of public health. This paper proposes a decision-making method of doctor-patient bilateral matching, which fully considers the actual demands of doctors and patients in the process of diagnosis and treatment. Firstly, based on the different evaluation forms and index properties, the satisfaction calculation formulas of three evaluation types: clear number, interval number and language short sentence and two index properties of cost type and benefit type are defined. Then, taking the maximization of satisfaction between doctors and patients, the maximization of the number of patients receiving diagnosis and treatment and the minimization of workload difference between doctors as the decision-making objectives, the multi-objective decision-making model is constructed and solved by NSGA-II algorithm. Finally, it is proved that NSGA-II algorithm has better performance in solving the problem of doctor-patient bilateral matching by comparing the convergence, stability of solution distribution and running time of NSGA-II and NSGA-III algorithm.

At the same time, the research of this paper also has deficiencies, which need to be further deepened and improved in the future research. After using the matching method in this paper, there are still patients who have not been matched successfully. This paper does not study how to allocate these patients who have not been matched successfully. Therefore, the allocation of patients with matching failure will be further considered in future studies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JH is the main provider of the research ideas and is responsible for the control of the research process, progress, and model construction. WZ is the main writer of the paper and responsible for simulation. HG is mainly responsible for sorting out literature review and algorithm selection. All authors contributed to the article and approved the submitted version.

Conflict of interest

WZ, JH, and HG were employed by Huaxin Consulting Co., Ltd.

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Study on sustainable development of pharmaceutical health industry under ecological coordination

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Particularly in the post-pandemic period, where public health emergencies offer a greater risk of supply disruptions, the operational hazards of pharmaceutical supply chains are uncertain. One of the main concerns for businesses is how to handle the risk of supply disruption and take the necessary precautions to lower the chance of loss. Pharmaceutical raw material suppliers, pharmaceutical manufacturers and medical institutions constitute a complete three-tiered supply chain. On the basis of this, in Materials and methods part, a share contract based on buyback proceeds is created as a result, and a combination contract based on centralized decision-making and decentralized decision-making is employed to maximize the order volume of pharmaceutical supply chain participants. An out-of-stock cost pharmaceutical supply chain model is created, and a related solution is provided and measurable examples. In Results and discussion part, to confirm the accuracy of the model and algorithm, numerical examples are employed. Buyback prices and order volumes were subjected to sensitivity analysis, and discussion is had over how various parameters affect a model's performance. Due to supply disruptions, the study's findings show that there is "double sourcing" between upstream pharmaceutical raw materials and downstream major suppliers, necessitating the establishment of a supply chain with numerous standby suppliers. At the same time, modifying the contract parameters can improve the supply motivation of backup suppliers and guarantee the profitability of downstream medical institutions.

KEYWORDS

ecological coordination, pharmaceutical health industry, supply chain, risk disturbance, sustainability, combined contract

Introduction

The century epidemic and the century of transition that the world is currently experiencing are interwoven, causing instability and uncertainty on a worldwide scale. The global supply chain is forced into the reconstruction stage as a result of geopolitical disputes and numerous trade restrictions (1). The COVID-19 outbreak has caused a severe global shortage of medical supplies, a significant disruption in the pharmaceutical supply chain, uncertainty regarding the fundamental safety of medical staff, and the inability to treat a significant number of affected patients promptly. Governments and pharmaceutical companies, therefore, pay more attention to the risk of supply chain disruption against the backdrop of the increasingly complex and variable external environment and work to adopt targeted strategies to improve their capacity to withstand risks, which is of great significance to ensure the normal functioning of pharmaceutical supply chains (2). This paper examines the risk of supply disruption in the pharmaceutical supply chain. A combination contract model is built based on the study of member income under various decision-making models to investigate how to optimize and coordinate the pharmaceutical supply chain and address the supply interruption issue.

The relevant literature in pharmaceutical supply chain research mainly deals with the mode of operation, risk assessment, and sustainable development. Zhang et al. (3) realized the full life cycle management of medicine by building a monitoring system based on blockchain and deep learning. Salehi et al. (4) used data envelopment analysis (DEA) and fuzzy data envelopment analysis (FDEA) methods to assess pharmaceutical supply chain elasticity. In the risk assessment of the drug distribution supply chain, Zhang et al. (5) discussed multi-attribute decision-making with fuzzy bipolar Hamach correlation mean (BFHCA) operator. The different risks facing green supply chain development in the pharmaceutical industry were empirically analyzed by Kumar et al. (6) and different countermeasures were put forth. Halim et al. (7) constructed the supply chain network of sustainable drugs based on a decision support framework and system and verified and analyzed it with enterprise examples. Liu et al. (8) constructed a system dynamics model considering government dynamic penalties and subsidies for the evolutionary stability strategy of medical device recycling enterprises.

In the research of supply interruption, scholars analyze the supply chain ordering strategy, inventory strategy, and coordination strategy from different perspectives. Olivares-Aguila et al. (9) introduced a system dynamics framework to observe the game behavior of supply chain members and evaluate the impact of supply interruption on supply chain performance. Bo et al. (10) studied the coordinated scheduling problem of multi-product manufacturing supply chain with delivery time constraints under supply chain disruption. Chakraborty et al. (11) while developing mathematical models of SC and SCB proved that retailers are always more willing to take advantage of the capacity advantages of standby suppliers under interrupted supply. Gupta et al. (12) explored the role of early sales strategies in supply chain financing during supply disruptions. Parast also found through empirical data testing that increased R&D investment significantly reduces the impact of environmental and process disruptions on supply chain performance (13). Supply chain contract also plays an important role in supply chain optimization and coordination. Typical supply chain contracts include revenue sharing, volume flexibility, buybacks, and wholesale price contracts (14, 15). Canbulut et al. (16) studied the role of different repo combinations in supply chain performance in a fuzzy demand environment based on credibility theory. Farhat et al. (17) introduced term repo contracts into the supply chain's multi-cycle optimal procurement decisions. Niederhoff et al. (18) reported the supply chain decision behaviors with different attitudes under the wholesale price–revenue sharing contract, and the results showed that the subject's risk preference rendered the revenue-sharing contract invalid. Canbulut et al. (19) believed that the combination of game theory and revenue-sharing contracts can better achieve the optimal equilibrium strategy between suppliers and retailers. Liu et al. (20) introduced the option contract into the supply chain system composed of the government and risk aversion suppliers and derived the optimal reserve decision of government and enterprise emergency supplies. He et al. (21), based on revenue sharing and price subsidy contracts, coordinated the supply chain system to achieve the optimal service integrator scheduling strategy.

Based on the previous literature review, supply disruption research focuses on how to reduce disruption risk, supply chain recovery (22), and risk assessment. There is little research on supply disruption in pharmaceutical supply chain operating scenarios. Meanwhile, it is found that multi-contracts formed by combination can realize supply chain coordination better than single contracts. To this end, a two-stage template of a pharmaceutical supply chain portfolio contract is constructed by introducing revenue-sharing and buyback contracts when supply disruption risk is considered. The reasonable contract parameters are obtained through the simulation of the example, so as to improve the profits of medical institutions and pharmaceutical manufacturers, as well as the supply willingness of backup suppliers, and ensure the stable coordination of the pharmaceutical supply chain.

Materials and methods

Model description and assumptions

In this study, we assume that in a three-tiered supply chain consisting of pharmaceutical raw material suppliers, pharmaceutical manufacturers, and medical institutions (Figure 1), there are two pharmaceutical raw material suppliers A and B, which provide the same quality products and services. Among them, the product price of pharmaceutical raw material supplier A is low, but it is prone to supply interruption risk, while the product price of pharmaceutical raw material supplier B is high but stable and reliable. Supplier A is the main supplier of medicine, the manufacturer orders here first, and supplier B is a backup supplier, only when supplier A cannot meet the demand of pharmaceutical manufacturers' orders, pharmaceutical manufacturers will order from supplier B. To improve the enthusiasm of pharmaceutical feedstock supplier B and reduce the shortage loss, the revenue sharing contract is introduced based on dual sourcing to stimulate supplier B to prepare more supplies. In parallel, pharmaceutical manufacturers and downstream medical institutions sign repurchase agreements to ensure the income of medical institutions and improve the overall performance of the pharmaceutical supply chain. The symbols used in the model are shown in Table 1.

To facilitate the model construction and supply chain coordination strategy analysis, the following hypotheses are proposed:

(1) All players in the pharmaceutical supply chain are fully rational and risk-neutral.

(2) There is $w_e > w_i > w_h > v$ to ensure the revenues of pharmaceutical manufacturers and pharmaceutical raw material suppliers A and B.

(3) There is $p > w_e, \gamma w_e > v$ to ensure the effectiveness of the repurchase contract and the revenue of medical institutions.

(4) Pharmaceutical manufacturers dominate, and pharmaceutical supplier B has sufficient supply capacity to meet the production needs of pharmaceutical manufacturers.

Construction of two basic models

The methods followed by Wang and Li (22) were used. To obtain the optimal order quantity and maximum revenue of the pharmaceutical supply chain under centralized and decentralized decision-making, a benchmark model is established under centralized as well as decentralized conditions. The evaluation criteria are based on two basic models to judge whether the combination contract

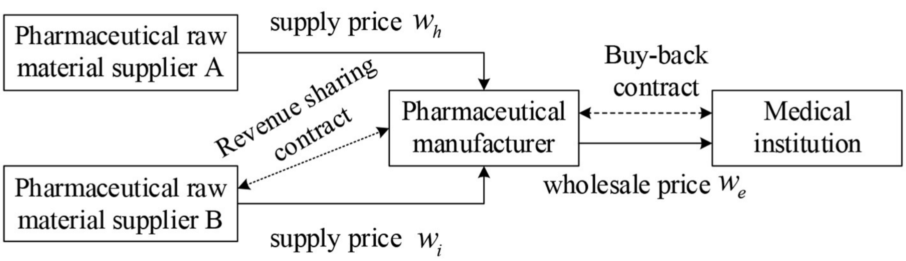

FIGURE 1
Operation process of the pharmaceutical supply chain under supply interruption.

TABLE 1 Model symbols and definitions.

Parameters	Definition
q_h	Supplier A's supply to pharmaceutical manufacturer
q_i	Supplier B's supply to pharmaceutical manufacturer
w_h	Supplier A's supply price to the pharmaceutical manufacturer
w_i	Supplier B's supply price to the pharmaceutical manufacturer
w_e	Wholesale prices of pharmaceutical manufacturer to medical institution
c_h	Unit product cost of supplier A
c_i	Unit product cost of supplier B
p	Medical sales price of medical institution
s	Shortage cost of medical institution
v	Residual value of unsold medicine
γ	Price coefficient of pharmaceutical manufacturer' repurchases from medical institution ($0 < \gamma < 1$)
κ	Revenue-sharing coefficient
θ	Probability of interruption risk of pharmaceutical backup supplier A($0 < \theta < 1$)
Q	Order quantity of medical institution

can improve the supply capacity of the backup supplier B, reduce the shortage loss of pharmaceutical manufacturers and downstream medical institutions, and realize the optimization and coordination of the whole supply chain.

Operation of the pharmaceutical supply chain under a centralized decision

When the supply interruption risk occurs for the main supplier A, the total revenue of the pharmaceutical supply chain is:

$$\pi = p\min(q_i, x) + v\max(q_i - x, 0) - s\max(x - q_i, 0) - c_i q_i \quad (1)$$

When the main supplier A has no supply interruption risk, the total revenue of the pharmaceutical supply chain is:

$$\begin{aligned}\pi &= p\min(q_h + q_i, x) + v\max(q_h + q_i - x, 0) \\ &- s\max(x - q_h - q_i, 0) - c_h q_h - c_i q_i\end{aligned} \quad (2)$$

Then, the expected revenue function of the pharmaceutical supply chain is:

$$\begin{aligned}&E(\pi) = \theta[p\min(q_i, x) + v\max(q_i - x, 0) - s\max(x - q_i, 0) \\ &-c_i q_i] + (1-\theta) \\ &[p\min(q_h + q_i, x) + v\max(q_h + q_i - x, 0) - s\max(x - q_h \\ &-q_i, 0) - c_h q_h - c_i q_i]\end{aligned} \quad (3)$$

The above equation can be rewritten as:

$$\begin{aligned}&\pi = \theta\int_0^{q_i}[px + v(q_i - x) - c_i q_i]f(x)dx \\ &+\theta\int_{q_i}^{\infty}[pq_i - s(x - q_i) - c_i q_i]f(x)dx + \\ &1-\theta\int_0^{q_h+q_i}[px + v(q_h + q_i - x) - c_h q_h - c_i q_i]f(x)dx + \\ &(1-\theta)\int_{q_h+q_i}^{\infty}[p(q_h + q_i) - s(x - q_h - q_i) - c_h q_h - c_i q_i]f(x)dx\end{aligned} \quad (4)$$

The first and second derivatives of Equation (4) about q_i can be obtained as:

$$\begin{aligned}&\frac{\partial\pi}{\partial q_i} = (p - c_i + s) + (v - p - s)[\theta F(q_i) + (1-\theta)F(q_h + q_i)] \\ &\frac{\partial^2\pi}{\partial {q_i}^2} = (v - p - s)[\theta f(q_i) + (1-\theta)f(q_h + q_i)]\end{aligned} \quad (5)$$

It is easy to get $\frac{\partial^2\pi}{\partial {q_i}^2} < 0$, knowing (4) is a concave function about q_i, let $\frac{\partial\pi}{\partial q_i} = 0$, and get the optimal supply of backup supplier B to meet the conditions:

$$\theta F({q_i}^{c*}) + (1-\theta)F(q_h + {q_i}^{c*}) = \frac{c_i - p - +s}{v - p - s} \quad (6)$$

Similarly, the second derivative of q_h is <0, and the formula (4) is also a concave function about q_h, which has a maximum value. Let $\frac{\partial\pi}{\partial q_i} = 0$, $\frac{\partial\pi}{\partial q_h} = 0$, and the optimal order quantity of the pharmaceutical supply chain under centralized conditions is obtained as:

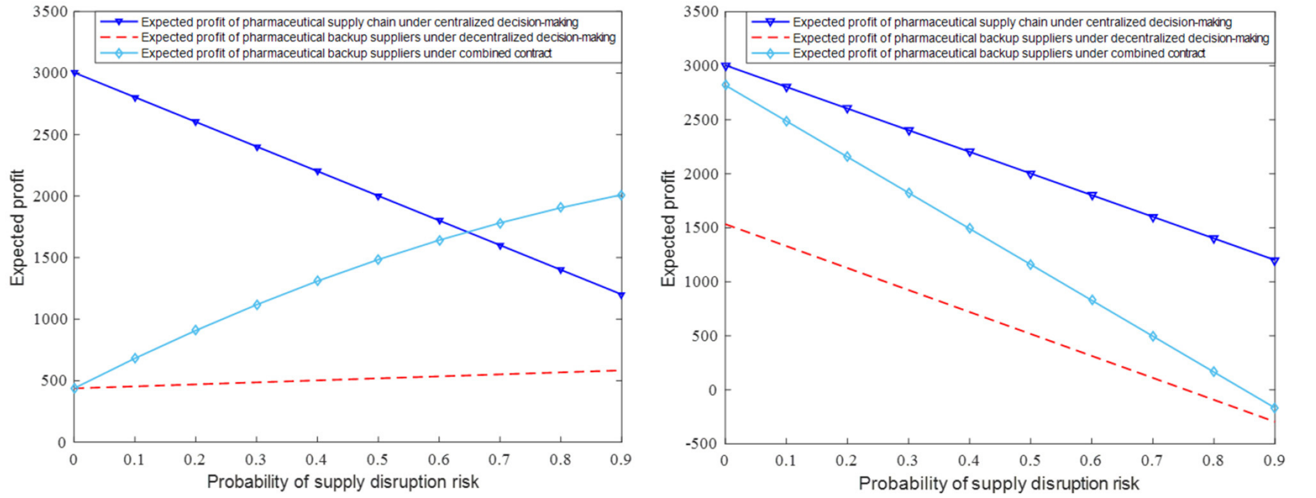

FIGURE 2
The impact of parameter θ on expected revenue of pharmaceutical backup suppliers and pharmaceutical manufacturer.

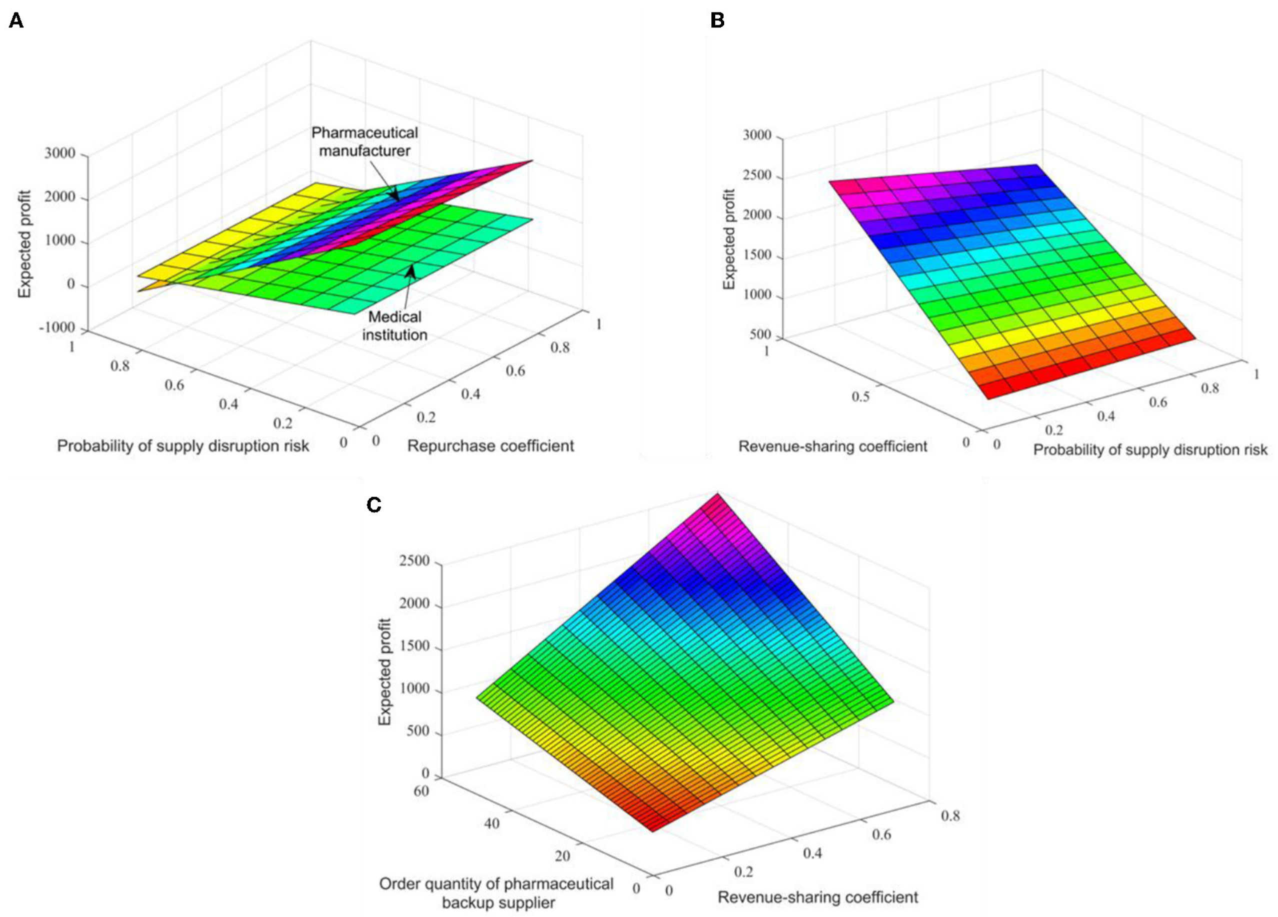

FIGURE 3
The impact of different contract parameters on the expected revenue of pharmaceutical supply chain members in figures **(A–C)**.

$$Q_C^* = q_h{}^* + q_i{}^{c*} = F^{-1}(\frac{c_h - p - s}{v - p - s}) \quad (7)$$

Analysis of Equation (7) and $F(x)$ characteristics concluded that the change of supply quantity $q_i{}^{c*}$ under centralized decision-making is closely related to the value v, that is, the greater the residual value of unsold drugs in pharmaceutical institutions, the greater the backup supplier B can provide more pharmaceutical raw materials; retaining the partial residual value of drugs not only compensates for the procurement losses of pharmaceutical manufacturers but also reduces the supply cost of backup supplier B. Furthermore, we calculated the partial derivative of Equation (5) with respect to θ and got $\frac{\partial^2 \pi}{\partial q_i \partial \theta} > 0$. It can be seen that q_i and θ change positively. When the supply interruption probability θ is greater, the supply volume of backup supplier B is greater. At this point, pharmaceutical companies prefer backup suppliers, because the more likely a major supplier A is to be disrupted, the more likely it is that there will be shortages of raw materials produced by pharmaceutical companies. To cope with the shortage loss caused by interruption, pharmaceutical manufacturers are increasingly relying on a more stable raw material backup supplier B to meet the needs of medical institutions and patients.

Operation of the pharmaceutical supply chain under a decentralized decision

Operation analysis of backup supplier:

To simplify the model calculation, let q_h be a fixed value. Under decentralized conditions, pharmaceutical raw material backup supplier B mainly relies on the classical newsboy model to determine the optimal supply quantity, and its supply capacity model is as follows:

$$\begin{aligned} L(q_i) &= (1-\theta)E\min[(x-q_h), q_i] + \theta E\min(x, q_i) \\ &= q_i - \theta\int_0^{q_i} F(x)dx - (1-\theta)\int_{q_h}^{q_h+q_i} F(x)dx \end{aligned} \quad (8)$$

Under the given production and supply capacity constraints of pharmaceutical raw material backup suppliers, the revenue function is as follows:

$$\begin{aligned} \pi_i(q_i) &= w_i L(q_i) + (1-\theta)[\int_{q_h}^{q_h+q_i} v(q_h+q_i-x)f(x)dx \\ &- \int_0^{q_h}(c_i - v)q_i f(x)dx \\ &- \int_{q_h}^{+\infty} c_i q_i f(x)dx] - \theta[\int_0^{q_i}[c_i - v(q_i - x)]f(x)dx \\ &+ \int_{q_i}^{+\infty} c_i q_i f(x)dx] \end{aligned} \quad (9)$$

The first and second derivatives of Equation (8) with respect to q_i are obtained as follows:

$$\frac{\partial \pi_i(q_i)}{\partial q_i} = w_i - c_i + [(1-\theta)F(q_h+q_i) + \theta F(q_i)](v - w_i) \quad (10)$$

$$\frac{\partial^2 \pi_i(q_i)}{\partial q_i{}^2} = [(1-\theta)f(q_h+q_i) + \theta f(q_i)](v - w_i) < 0 \quad (11)$$

$$(1-\theta)F(q_h + q_i{}^{d*}) + \theta F(q_i{}^{d*}) = \frac{c_i - w_i}{v - w_i} \quad (12)$$

Operation analysis of pharmaceutical manufacturer is as follows:

$$\begin{aligned} &\pi_e(q_i) = (1-\theta)[\int_0^{q_h+q_i}[w_e x + v(q_h+q_i-x)]f(x)dx + \\ &\int_{q_h+q_i}^{+\infty}[w_e(q_h+q_i) - s(x-q_h-q_i)]f(x)dx] \\ &+\theta[\int_0^{q_i}[w_e x + v(q_i - x)f(x)]dx + \\ &\int_{q_i}^{+\infty}[q_i w_e - s(x-q_i)]f(x)dx] - w_i L(q_i) \end{aligned} \quad (13)$$

Derivation of formula (12) is:

$$\frac{\partial \pi_e(q_i)}{\partial q_i} = [\theta F(q_i) + (1-\theta)F(q_h+q_i)](w_i - w_e - s) + w_e - w_i \quad (14)$$

$$\frac{\partial^2 \pi_e(q_i)}{\partial q_i{}^2} = [\theta f(q_i) + (1-\theta)f(q_h+q_i)](w_i - w_e - s) \quad (15)$$

Let $\frac{\partial \pi_e(q_i)}{\partial q_i}$ be equal to 0 to get the equation:

$$\theta F(q_i) + (1-\theta)F(q_h+q_i) = \frac{w_i - w_e}{w_i - w_e - s} \quad (16)$$

According to the $F(x)$ characteristics, formula (15) is not valid, $\frac{\partial \pi_e(q_i)}{\partial q_i} > 0$ is constant. The revenue function $\pi_e(q_i)$ is a monotone increasing function of the supply quantity q_i of the backup suppliers, which the revenue of the pharmaceutical manufacturers increases with the increase of supply amount.

Operation analysis of medical institution:

Assuming that medical institutions do not sign any contracts with pharmaceutical manufacturers under decentralized decision-making, the expected revenue of medical institutions is:

$$\begin{aligned} &E(\pi_r) = \theta[p\min(q_i, x) + v\max(q_i - x, 0) - s\max(x - q_i, 0) \\ &-w_e q_i] + (1-\theta) \\ &[p\min(q_h+q_i, x) + v\max(q_h+q_i-x, 0) - s\max(x-q_i-q_h, 0) \\ &-w_e(q_h+q_i)] \end{aligned} \quad (17)$$

That is, the above formula can be rewritten as:

$$\begin{aligned} &\pi_r = \theta[\int_0^{q_i}[px + v(q_i - x) - w_e q_i]f(x)dx + \int_{q_i}^{\infty}[pq_i - s(x-q_i) \\ &-w_e q_i]f(x)dx] + \\ &(1-\theta)[\int_0^{q_h+q_i}[px + v(q_h+q_i-x) - w_e(q_h+q_i)]f(x)dx + \\ &\int_{q_h+q_i}^{\infty}[p(q_h+q_i) - s(x-q_h-q_i) - w_e(q_h+q_i)]f(x)dx] \end{aligned} \quad (18)$$

According to the same principle of Equation (5), the revenue function π_r is a concave function q_h, q_i. Let $\frac{\partial \pi_r}{\partial q_i} = 0, \frac{\partial \pi_r}{\partial q_h} = 0$, the optimal order quantity of medical institutions can be obtained as follows:

$$Q^* = q_h{}^* + q_i{}^* = F^{-1}(\frac{w_e - p - s}{v - p - s}) \quad (19)$$

Based on the above analysis, under decentralized decision-making, pharmaceutical manufacturers and medical institutions jointly rely on pharmaceutical main supplier A and backup supplier

B to provide raw material products to meet the needs of production and patients. Comparing Equation (16) with Equation (12), it is found that the supply backup supplier B is much larger in centralized decision-making than in decentralized decision-making because backup suppliers usually provide fewer goods in accordance with their own interests, which leads to the failure of the pharmaceutical supply chain to achieve global optimization. Meanwhile, it is found that pharmaceutical manufacturers' revenue is positively correlated with the supply of backup suppliers. When backup suppliers can provide a steady supply of raw materials and products, pharmaceutical companies can further improve their revenues.

Pharmaceutical supply chain coordination strategy under portfolio contract

In the operation of the pharmaceutical supply chain, major suppliers are at risk of supply disruptions due to cumbersome transportation processes and random factors of substandard raw material quality. At this time, pharmaceutical manufacturers will increase orders to backup supplier B to cope with the loss of production due to shortages of pharmaceutical ingredients. Thus, to realize the smooth operation of the supply chain, upstream enterprises will sign repurchases or revenue-sharing contracts with downstream enterprises, reduce shortage loss caused by supply interruption risk, improve supply enthusiasm of backup suppliers, and realize revenue maximization of each participant.

Ordering strategy of the medical institution under repurchase contract

The pharmaceutical supply chain has a much higher operational risk than the normal supply. To realize the downstream supply chain optimization and coordination, reduce the storage and sale costs of medical institutions when supply exceeds demand, recover cash flow, and reduce the concerns of large-scale supply, medical institutions will enter repurchase agreements with pharmaceutical companies. There are still two cases of supply interruption and non-interruption, and the following revenue function of medical institutions is obtained:

$$E(\pi_r') = \theta[p\min(q_i,x) + \gamma w_e \max(q_i - x, 0) - s\max(x - q_i, 0) - w_e q_i] + (1-\theta)[p\min(q_h + q_i, x) + \gamma w_e \max(q_h + q_i - x, 0) - s\max(x - q_i - q_h, 0) - w_e(q_h + q_i)] \tag{20}$$

The above formula can be rewritten as:

$$\pi_r{}^m = \theta[\int_0^{q_i}[px + \gamma w_e(q_i - x) - w_e q_i]f(x)dx + \int_{q_i}^{\infty}[pq_i - s(x-q_i) - w_e q_i]f(x)dx] + (1-\theta)[\int_0^{q_h+q_i}[px + \gamma w_e(q_h + q_i - x) - w_e(q_h+q_i)]f(x)dx + \int_{q_h+q_i}^{\infty}[p(q_h+q_i) - s(x - q_h - q_i) - w_e(q_h+q_i)]f(x)dx] \tag{21}$$

The optimal order quantity of medical institutions under the repurchase contract can be obtained by calculating the derivatives q_h and q_i, respectively:

$$Q^* = q_h{}^* + q_i{}^* = F^{-1}(\frac{w_e - p - s}{\gamma w_e - p - s})$$

Revenue of pharmaceutical manufacturers under combined contract

Under this scenario, the expected revenue of the pharmaceutical manufacturer is:

$$E(\pi_e{}^m) = \theta[w_e\min(q_i,x) - s\max(x-q_i,0) + (v - \gamma w_e)\max(q_i - x, 0) - w_i q_i] + (1-\theta)[w_e\min(q_h+q_i,x) - s\max(x - q_i - q_h, 0) + (v-\gamma w_e)\max(q_h + q_i - x, 0) - w_i q_i - w_h q_h] \tag{22}$$

Rewrite the above formula in integral form as follows:

$$\pi_e{}^m = \theta\int_0^{q_i}[w_e x + (v-\gamma w_e)(q_i - x) - w_i q_i]f(x)dx + \theta\int_{q_i}^{+\infty}[w_e q_i - s(x-q_i) - w_i q_i]f(x)dx + (1-\theta)\int_0^{q_h+q_i}[w_e x + (v - \gamma w_e)(q_h + q_i - x) - w_i q_i - w_h q_h]f(x)dx + (1-\theta)\int_{q_h+q_i}^{+\infty}[w_e(q_h + q_i) - s(x - q_h - q_i) - w_i q_i - w_h q_h]f(x)dx \tag{23}$$

Similarly, we can get:

$$\frac{\partial\pi'}{\partial q_i} = (v - \gamma w_e - w_e - s)[(1-\theta)F(q_h+q_i) + \theta F(q_i)] + w_e + s - w_i \tag{24}$$

$$\frac{\partial^2\pi'}{\partial q_i{}^2} = (v - \gamma w_e - w_e - s)[(1-\theta)f(q_h + q_i) + \theta f(q_i)] \tag{25}$$

From these assumptions, we can easily know that $\frac{\partial^2\pi'}{\partial q_i{}^2} < 0$ is constant, and the satisfying conditions of the optimal order quantity $q_i{}^*$ are obtained as follows:

$$(1-\theta)F(q_h + q_i{}^*) + \theta F(q_i{}^*) = \frac{w_i - w_e - s}{(v - \gamma w_e - w_e - s)} \tag{26}$$

Revenue of pharmaceutical backup supplier under combined contract

The revenue obtained by the pharmaceutical manufacturer from the main supplier A of pharmaceutical raw materials is recorded as π_{e1}, and the revenue obtained from the backup supplier B of pharmaceutical raw materials is recorded as π_{e2}.

$$\pi_{e1}(q_h) = (1-\theta)[\int_0^{q_h}[w_e x f(x)dx + \int_{q_h}^{+\infty}[w_e q_h f(x)dx + \int_0^{q_h} v(q_h - x)f(x)dx - \int_{q_h}^{q_h+q_1} s(x-q_h)f(x)dx] - \theta\int_{q_1}^{+\infty} sxf(x)dx \tag{27}$$

$$\pi_{e2}(q_i) = \pi_e{}^m(q_i) - \pi_{e1}(q_h) \tag{28}$$

With a revenue sharing factor κ, pharmaceutical manufacturers share their revenues from the backup supplier π_{e2} to the backup supplier. The revenue function of the backup supplier under the combination contract is obtained as follows:

$$\pi_i{}^n = \pi_i + \kappa(\pi_e{}^m - \pi_{e1}) \tag{29}$$

Bring Equations (9), (23), and (27) into the above formula and derive q_i to obtain:

$$\frac{\partial \pi_i{}^n}{\partial q_i} = [(v - w_i) + \kappa(v - \gamma w_e - w_e - s)][(1-\theta)F(q_h + q_i) + \theta F(q_i)] + \kappa(w_e + s - w_i) + (w_i - c_i) \tag{30}$$

$$\frac{\partial^2 \pi_i{}^n}{\partial q_i{}^2} = [(v - w_i) + \kappa(v - \gamma w_e - w_e - s)][(1-\theta)f(q_h + q_i) + \theta f(q_i)] < 0 \tag{31}$$

That is, after joining the revenue-sharing contract, the backup supplier has the maximum revenue and $\pi_i{}^n(q_i{}^{n*})$ meets the following formula:

$$(1-\theta)F(q_h + q_i{}^{n*}) + \theta F(q_i{}^{n*}) = \frac{c_i - w_i - \kappa(w_e + s - w_i)}{(v - w_i) + \kappa(v - \gamma w_e - w_e - s)} \tag{32}$$

Proposition: The income sharing coefficient κ should be valued at the interval

$$[\frac{\pi_i(q_i{}^*) - \pi_i(q_i{}^{n*})}{\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)}, \frac{\pi_e(q_i{}^{n*}) - \pi_e(q_i{}^*)}{\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)}].$$

Proof: If the pharmaceutical manufacturer and the backup supplier sign a revenue-sharing contract to achieve coordination of the contract, it is necessary to ensure that after the pharmaceutical producer and backup supplier join the contract, their respective benefits are no less than under decentralized conditions.

$$\pi_e{}^n(q_i{}^{n*}) = \pi_e(q_i{}^{n*}) - \kappa[\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)] \geq \pi_e(q_i{}^*) \tag{33}$$

$$\pi_i{}^n(q_i{}^{n*}) = \pi_i(q_i{}^{n*}) + \kappa[\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)] \geq \pi_i(q_i{}^*) \tag{34}$$

Combining Equations (33) and (34), the value range of κ can be obtained as follows:

$$\frac{\pi_i(q_i{}^*) - \pi_i(q_i{}^{n*})}{\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)} \leq \kappa \leq \frac{\pi_e(q_i{}^{n*}) - \pi_e(q_i{}^*)}{\pi_e(q_i{}^{n*}) - \pi_{e1}(q_h)} \tag{35}$$

when κ is within the above range, the backup supplier's supply $q_i{}^{n*}$ is closer to the supply $q_i{}^{c*}$ under the centralized condition, which is much larger than the supply $q_i{}^{d*}$ under the decentralized condition. The revenues of backup suppliers, pharmaceutical manufacturers, and medical institutions are not less than their respective revenues under decentralized conditions, which shows that the combination contract based on buyback-benefit sharing can coordinate the pharmaceutical supply chain under an interruption crisis and achieve Pareto improvement.

Results and discussion

To verify the effectiveness of the mathematical model built earlier, a correlation analysis of each parameter is performed. These parameters are chosen as follows:$c_i = 10$,$c_h = 8$,$w_i = 20$,$w_h = 15$,$w_e = 25$,$p = 40$,$s = 20$,$v = 5$, and the random market demand follows the distribution of $N(100, 10^2)$.

When $\gamma = 0.91$ and $\kappa = 0.3$, we obtain the expected revenue performance of the whole pharmaceutical supply chain and members under different scenes when the supply interruption risk probability is in the interval $(0, 0.9)$, as shown in Figure 2. It can be seen that the expected revenues of pharmaceutical producers have decreased and those of the standby suppliers of pharmaceutical raw materials have increased as the probability of supply interruption has increased. This is due to the high risk of interruption from major suppliers and the increased procurement cooperation between pharmaceutical manufacturers and backup suppliers, which allows stable backup suppliers to be protected from supply interruptions and thus achieve higher returns. In addition, it can be found that the revenue when the drug manufacturer and the backup supplier sign the merger contract will be much higher than the revenue when the decentralized decision is made so that the pharmaceutical supply chain can be optimized and coordinated.

When $q_i = 60$ and $q_h = 50$, the impact of different contract parameter combinations (γ, κ, θ) on the expected revenue of the pharmaceutical supply chain members is shown in Figures 3A, B. In comparison, the repurchase coefficient has little effect on the expected revenue of pharmaceutical manufacturers and medical institutions. Pharmaceutical manufacturers' expected revenue slightly decreases with the increase of the repurchase coefficient, while medical institutions' expected revenues slightly increase. Figure 3B shows that with the increase of the coefficient of revenue sharing, the expected revenue of backup suppliers will also increase significantly. This is because even if pharmaceutical manufacturers increase the recovery price coefficient, the recovery price is still low, which can only make up for some losses in medical institutions. To encourage backup suppliers to supply, pharmaceutical manufacturers have obvious revenue advantages in signing revenue-sharing contracts.

Assuming that $\theta = 0.3$, the changes in expected revenues and supply volume of pharmaceutical raw material backup suppliers within the range $(0.1, 0.9)$ of income sharing coefficient are shown in Figure 3C. Thus, an increase in the revenue distribution factor will increase the expected revenues and supply of backup suppliers, that is, the number of orders placed by pharmaceutical companies. Practice shows that the combination contract can optimize the coordination of the pharmaceutical supply chain, and there is an optimal ordering strategy to make the pharmaceutical supply chain profitable to the level of centralized decision-making.

Conclusion

In this study, we constructed a three-tiered supply chain composed of pharmaceutical raw material suppliers, pharmaceutical manufacturers, and institutions. Assuming that the market demand follows a random distribution, pharmaceutical manufacturers complete the production objectives and meet the needs of patients through a joint supply of a major supplier and a backup supplier. There is a large shortage cost in downstream medical institutions. Once the supply cannot meet the needs of patients, medical institutions will bear huge punishment costs and produce shortage losses. By introducing repurchase contracts between medical institutions and pharmaceutical manufacturers and introducing revenue-sharing contracts between backup suppliers and pharmaceutical manufacturers, it is proved that the corresponding combined contracts can increase the supply of backup suppliers and meet the needs of the pharmaceutical market, effectively respond to the supply interruption crisis of the main supplier, significantly improve the revenues of medical institutions and backup suppliers, and achieve the purpose of supply chain coordination. It is enlightening that pharmaceutical manufacturers need to cooperate with backup suppliers and medical institutions in a wider field and at a higher level in practice to reduce the risk of supply interruption of the main suppliers.

In addition, this paper has the following shortcomings: generally, in the actual operation of the pharmaceutical supply chain, a pharmaceutical manufacturer may articulate more than one pharmaceutical organization, or a pharmaceutical raw material supplier serves more than one pharmaceutical manufacturer, and this study only considers the pharmaceutical supply chain members. Therefore, in the future, we should consider studying the sustainable development model of a complex supply chain ecosystem with multiple levels and multiple subjects.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GF conceived the model and project. ZZ analyzed results and wrote the manuscript. All authors read, edited, and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact of environmental education on environmental quality under the background of low-carbon economy

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Introduction: How does environmental education affect environmental quality? There is no consensus among theorists. This paper is devoted to exploring the influence mechanism of environmental education and environmental quality under the background of a low-carbon economy from a theoretical model and empirical analysis.

Methods: The research method of this paper includes two aspects. First, from the consideration of the central planner, this paper draws on and improves the Ramsey Model to explore the interaction mechanism among environmental education, environmental quality and green growth. Second, this paper uses provincial panel data from China from 2011 to 2017 for empirical analysis, which mainly verifies the impact mechanism of environmental education on environmental quality.

Results and discussion: The theoretical model shows that environmental education enhances green consumption intention through residents' environmental awareness and enhances enterprises' cleaner production motivation through environmental pressure. Correspondingly, the pressure to improve environmental quality will also promote the economy's endogenous growth through the digital economy's transformation and the accumulation of human capital. The empirical analysis confirms that environmental education can improve environmental quality through green consumption and pollution control. Still, the effect of improving environmental quality only through pollution control is not apparent, and pollution control needs to be combined with environmental education, especially in high-pollution areas. Finally, this paper puts forward some suggestions for optimizing environmental education.

KEYWORDS
low-carbon economy, environmental health education, pollution control, household consumption, environmental quality

Introduction

Global climate change has become one of the most significant challenges to human development, dramatically promoting global political consensus and significant actions to address climate change. At the first World Summit on Sustainable Development (WSSD) in Johannesburg in 2002, delegates called for "encouraging and promoting the development of a 10-year framework for Sustainable Consumption and Production Plans (SCP) to support regional and national initiatives to accelerate the transition to SCP". Promoting sustainable development through pollution control and green consumption is increasingly becoming the international community's consensus.

When the level of economic development reaches a certain stage, the government should pay more attention to sustainable development in public life, education, and environmental protection (1). In recent years, more and more governments have also elevated "carbon neutrality" as a national strategy, committed to the vision of a carbon-free future through environmental education, pollution control, and green consumption. The European Union has taken the lead in announcing an absolute target to cut greenhouse gas emissions by at least 55% from 1990 levels by 2030 and make Europe the world's first "carbon neutral" continent by 2050. China has pledged to stop increasing its carbon dioxide emissions by 2030 and gradually reduce them after peaking, setting a strategic goal of achieving carbon neutrality by 2060. In 2021, the Opinions of the CPC Central Committee and the State Council on Fully, Accurately, and Comprehensively Implementing the New Development Concept to achieve carbon peak and neutrality began to be issued nationwide. The Opinions set a "timetable" and "road map" for achieving carbon peak and neutrality. It is a major measure for China to promote high-quality development, strengthen ecological civilization construction, safeguard national energy security and build a community with a shared future for humanity.

Economic growth is becoming more and more dependent on the natural environment. Scholars have paid more and more attention to the relationship between economic growth and sustainable development of the natural environment (2, 3). In the initial stage of economic growth, industrialization usually brings serious environmental pollution, such as air pollution, water and soil environmental pollution (4); this phenomenon also exists in China (5). With the improvement of the industrialization process, sustainable and high-quality development is the new theme of China's current economy and society. If we still blindly pursue economic growth rate, ignoring environmental carrying capacity and "trading pollution for GDP," which ran counter not only to the concept of sustainable development but also the goal of high-quality economic development.

Existing studies found that environmental education affects environmental quality. On the one hand, environmental education increases the environmental awareness of residents or consumers, forcing local pollution control and environmental legislation to improve environmental quality (6). On the other hand, environmental education promoted green consumption (7) and thus reduced pollution control. However, some scholars believe that the impact of pollution control on environmental quality is uncertain (8, 9). Is pollution control the core channel through which environmental education affects environmental quality? There is no consensus among theorists. Therefore, this paper aims to theoretically analyze and empirically test the transmission path and influence mechanism of environmental education, green consumption, green production, pollution control, and other factors on environmental quality.

The rest of this paper is arranged as follows: The second part is a literature review and theoretical hypotheses. The third part is theoretical model analysis. The fourth part is empirical analysis. The conclusion and discussion are presented in the last section.

Literature review and research hypotheses

Sustainable development effects of environmental education

The role of education investment in sustainable development has attracted more and more attention from the academic community. Education can reduce carbon emissions, and designing a comprehensive policy framework to define sustainable development is an issue facing most countries worldwide (10). International experience shows that education and sustainable development are closely linked and that environmental education is integral to achieving sustainable development (11). Environmental education has an impact on environmental quality (12, 13).

Some studies have found that educational institutions are increasingly important in driving sustainable development. Nomura (14) studied the historical development of environmental education in Indonesia and found that education for sustainable development plays an important role in social politics, cultural freedom, and poverty eradication. Zafar et al. (10) empirically verified that the environmental quality of a region is significantly affected by the education level of residents. Getting higher education can help students rethink the role of human beings on the planet to deal with significant challenges related to sustainability (15). Azeiteiro et al. (16) surveyed 1,257 students from Portuguese public higher education institutions *via* an online questionnaire. They found that most students with education in sustainable development are more concerned about climate change and are more inclined to reuse, reduce and recycle waste. Another group of students contributes to sustainable development by participating in activities organized by environmental organizations or higher education institutions, such as environmental protection or community volunteering. Based on Australian higher education data from 1950 to 2014, Balaguer and Cantavella (6) found that the increase in per capita income and education level has been proven to be effective in reducing pollution emissions. Therefore, we propose the following:

H1: Environmental education has a positive impact on environmental quality.

Influence mechanism of environmental education

Many scholars have analyzed the transmission mechanism of environmental education to sustainable development from green consumption and pollution control perspectives. Firstly, from the standpoint of consumption, relevant scholars have found that environmental education can enhance their awareness of green consumption. Publicity and education remain the primary interventions for promoting green consumption (17). Environmental education can impact consumers' willingness to consume green products by influencing consumers' environmental ethics, moral obligations, and environmental attitudes (7). Jin and Li (18) found that environmental education can effectively increase the incentives, willingness, and amount of individuals to pay for pro-environmental behaviors. Hoffman and Muttarak (19) found an association between education and pro-environmental behavior, and that education influences behavior mainly by raising awareness of anthropogenic causes of climate change. Meyer (20) found that education makes individuals pay more attention to social welfare and act more environmentally friendly by employing European data samples. Hoang (21) took Da Nang City, Vietnam, as an example, studied the impact of environmental education at the elementary level on sustainable development, and found that environmental education has significantly increased students' knowledge of solid waste management and improved environmental awareness. Educational institutions positively exported environmental protection and sustainable development courses to trainees (22).

Secondly, from the perspective of production, relevant scholars have found that environmental education can enhance enterprises' awareness of green production. The mainstream view is that pollution control can improve environmental quality, and green innovation and energy investment positively affect environmental quality. Based on Chinese provincial data, Guo et al. (23) found that income, environmental innovation, investment in the energy industry, and renewable energy consumption were critical factors in explaining CO2 emissions. Corporate innovation has significantly increased corporate environmental investment, and the regulatory effect of environmental policy is positive and significant (24). Zhou et al. (25) demonstrated that firms with highly educated CEOs are more likely to engage in environmental innovation and green production, especially when they operate in areas with severe environmental stress. At the same time, consumer environmental awareness will encourage enterprises to increase cleaner production (25). Li and Lv (26) believed that the value of consumers' environmental awareness would significantly impact the investment in environmental innovation of monopolistic manufacturers. The environmental protection industry plays a crucial role in the green economy. Fan et al. (8) analyzed the impact of investment in the environmental protection industry on the national economy from the perspective of input-output. They found that the environmental protection industry can effectively promote the national economy and employment and drive the development of other industries, especially manufacturing. King (27) even proposed that the aid of the United Nations and international organizations to backward countries and regions should not be limited to material aid but should popularize education to ensure sustainable economic development.

Thus, we believe that the impact of environmental education on environmental quality is mainly based on two channels: upgrading residents' consumption and increasing pollution control. The following hypotheses are proposed:

H2a: Residents' consumption level will affect the quality of the environment, so it is necessary to improve the promoting effect of environmental education on environmental quality by improving residents' environmental awareness or upgrading green consumption.

H2b: Green technology innovation will affect environmental quality, so it is necessary to improve the promoting effect of environmental education on environmental quality by improving the cleaner production capacity of enterprises or pollution control.

Synergistic mechanism of environmental education and pollution control

The current views also hold that whether environmental education can improve environmental quality is still uncertain. Powdthavee (9) found that there is no evidence that changes in the minimum school age in England and Wales significantly impact individuals' environmental tendencies; that is, increasing the number of years of general education has no significant impact on people's environmental awareness. It is different whether pollution control is a pre-emptive action or a remedial measure that affects environmental quality. When pollution control is remedial, the control effect is insignificant. Because pollution problems are discovered, more environmental issues have become icebergs hidden under the sea. If pollution control is a preemptive action, the improvement in environmental quality is noticeable. On the whole, investment in environmental education indirectly impacts the progress of environmental quality, which has become the academic consensus; environmental education will affect pro-environmental behavior, but not directly. It is to improve environmental quality in an indirect way, such as knowledge-concern-willingness (28).

Li et al. (1) found that green innovation, clean energy investment, and education improve environmental sustainability in the long run. Still, short-term estimates vary and suggest governments in highly polluting economies should increase investment in education, clean energy, and technology. Haque and Sharif (29) believed that relying solely on a large number of environmental protection legislation and investment plans for environmental management has no significant effect on reducing the increasing risk of environmental pollution in Bangladesh. Environmental education needs to be strengthened. Thus, we propose the following:

H3: It is not obvious to improve environmental quality only by relying on pollution control, which needs the support of environmental education, especially in highly polluted areas.

Theoretical model

Investment in environmental education can be regarded as an input element of production. The products are used for current consumption, investment in expanded reproduction in the next period, and investment in environmental quality in the next period. The investment accumulation will not be used for the next production period. From the consideration of the central planner, we draw on the Ramsey Model (30) and construct the following model to maximize the utility of consumers in each period:

$$\begin{aligned}&\text{Max} \sum_{t=0}^{\infty} \beta^t \ln c_t \\ &\text{s.t.} \quad k_0, e_0 \textit{ given} \quad c_t + k_{t+1} + e_{t+1} = (Ak_t^{\alpha} e_t^{\tau})^{\gamma}\end{aligned} \tag{1}$$

Where β is the intertemporal discount factor of consumption, $\beta \in (0,1)$. e represents the investment of environmental governance. c is the consumption. k is the investment. A is the technical efficiency, which is exogenous. α is the output elasticity of capital, $\alpha \in (0,1)$. τ is the output elasticity of environmental investment, $\tau \in (0,1)$. γ is the coordination between production and consumption, $\gamma \in [0,1]$. When the consumption structure is upgraded, the production or industrial structure is also upgraded and γ is larger. Thus, we assume that $k_{t+1} = \delta k_t^{\alpha\gamma} e_t^{\tau\gamma}$, $e_{t+1} = \vartheta\, k_t^{\alpha\gamma} e_t^{\tau\gamma}$.

We construct the Bellman Equation:

$$V\left(k_t, e_t\right) = {}^{max}_{c_t k_{t+1}}\{\ln c_t + \beta V(k_{t+1}, e_{t+1})\} \tag{2}$$

The simplified Bellman equation is as follows:

$$V\left(k_t, e_t\right) = {}^{max}_{k_{t+1}, e_{t+1}}\{\ln(A^{\gamma} k_t^{\alpha\gamma} e_t^{\tau\gamma} - k_{t+1} - e_{t+1}) + \beta V(k_{t+1}, e_{t+1})\} \tag{3}$$

From formula (3), we derive first-order derivation of k_{t+1} and k_t in Bellman Equation:

$$k_{t+1}: \quad \frac{1}{A^{\gamma} k_t^{\alpha\gamma} e_t^{\tau\gamma} - k_{t+1} - e_{t+1}} = \beta V_1\left(k_{t+1}, e_{t+1}\right) \tag{4}$$

$$k_t: \quad V_1\left(k_t, e_t\right) = \frac{A^{\gamma} \alpha\gamma k_t^{\alpha\gamma-1} e_t^{\tau\gamma}}{A^{\gamma} k_t^{\alpha\gamma} e_t^{\tau\gamma} - k_{t+1} - e_{t+1}} \tag{5}$$

Bringing $k_{t+1} = \delta k_t^{\alpha\gamma} e_t^{\tau\gamma}, e_{t+1} = \vartheta k_t^{\alpha\gamma} e_t^{\tau\gamma}$ into formulas (4) and (5), we have:

$$\delta = A^{\gamma} \beta\alpha\gamma \tag{6}$$

Similarly, we derive first-order derivation of e_{t+1} and e_t in Bellman Equation from formula (3):

$$e_{t+1}: \quad \frac{1}{A^{\gamma} k_t^{\alpha\gamma} e_t^{\tau\gamma} - k_{t+1} - e_{t+1}} = \beta V_2\left(k_{t+1}, e_{t+1}\right) \tag{7}$$

$$e_t: \quad V_2\left(k_t, e_t\right) = \frac{A^{\gamma} \tau\gamma k_t^{\alpha\gamma} e_t^{\tau\gamma-1}}{A^{\gamma} k_t^{\alpha\gamma} e_t^{\tau\gamma} - k_{t+1} - e_{t+1}} \tag{8}$$

Bringing $k_{t+1} = \delta k_t^{\alpha\gamma} e_t^{\tau\gamma}, e_{t+1} = \vartheta k_t^{\alpha\gamma} e_t^{\tau\gamma}$ into formulas (7) and (8), we have:

$$\vartheta = \mathrm{A}^{\gamma} \beta\tau\gamma \tag{9}$$

Therefore, in the equilibrium path, we have the following:

$$\mathrm{k}_{t+1} = \mathrm{A}^{\gamma} \beta\alpha\gamma \mathrm{k}_t^{\alpha\gamma} \mathrm{e}_t^{\tau\gamma} \tag{10}$$

$$\mathrm{e}_{t+1} = \mathrm{A}^{\gamma} \beta\tau\gamma \mathrm{k}_t^{\alpha\gamma} \mathrm{e}_t^{\tau\gamma} \tag{11}$$

$$\mathrm{c}_{t+1} = (1 - \beta\alpha\gamma - \beta\tau\gamma)\mathrm{A}^{\gamma} \mathrm{k}_t^{\alpha\gamma} \mathrm{e}_t^{\tau\gamma} \tag{12}$$

Formula (10)–(12) show that with increased investment in education, investment in environmental governance will also increase. This is conducive to raising the level of capital accumulation, which in turn promotes economic growth. Correspondingly, economic growth will lead to increased investment in environmental education. The increase in investment in environmental education will not only activate citizens' awareness of environmental protection (6, 20, 21) and the rule of law (29) but also urge the government and enterprise departments to pay more attention to environmental regulation and the supply of ecological and green products (23, 26).

Formulas (10)–(12) also show that the performance of environmental education investment is highly correlated with the coordination degree of production and consumption; When the product (or industrial) structure upgrading is more consistent with the consumption structure upgrading, that is, when the value of γ is larger, the investment in environmental education is more conducive to the upgrading of household consumption, economic growth, and the improvement of environmental quality.

Figure 1 shows that economic growth drives the improvement of environmental education. Environmental education raises residents' awareness of environmental protection. Residents resisted pollution and forced the government to implement environmental legislation and control environmental pollutants. At the same time, as consumption upgrades, consumption has become more and more prominent in green consumption and ecological consumption, which promotes green production ecological production, which is conducive to reducing pollutant emissions during production and improving environmental quality. The improvement of environmental quality provides a good atmosphere for production and consumption. It is conducive to accumulating human capital, which acts on the production process and promotes economic growth. Correspondingly, the improved environmental quality and the measures to promote it are conducive to transforming from a traditional economy to a digital economy and enterprises' adherence to low-carbon and sustainable development. Both digital economy and sustainable development are conducive to the endogenous growth of the economy through the accumulation of human capital, which is also a higher form of economic growth mode, that is, to realize the upgrading and transformation of economic development mode.

Empirical analysis

Variables

Dependent variable

Comprehensive Pollution Index (pl) serves as the explanatory variable in this study. Existing studies have mainly used single pollutant emission indicators as a substitute for environmental pollution, such as nitrogen oxides and sulfur dioxide (31). Industrial solid waste, industrial wastewater, soot, and domestic garbage are important factors affecting environmental quality (32–35). Entropy weight method can effectively investigate the change degree of each index and objectively reflect its importance. It can construct a pollution index with six secondary indexes, including nitrogen oxide, sulfur dioxide, industrial solid waste, industrial wastewater, soot, and household waste. The specific calculation method is as follows:

Step 1: Normalize pollution indicators.

$$y_{ij} = \frac{x_{ij} - \min(x_{1j} \cdots x_{nj})}{\max(x_{1j} \cdots x_{nj}) - \min(x_{1j} \cdots x_{nj})} \tag{13}$$

Where x_{ij} is the i-th sample under the j-th pollution index, and y_{ij} is the normalized sample.

Step 2: We calculate the weight of y_{ij}.

$$p_{ij} = y_{ij} / \sum_{i=1}^{n} y_{ij} \tag{14}$$

Step 3: We calculate the entropy value of the pollution index.

$$e_j = -\frac{\sum_{i=1}^{n} p_{ij} \ln(p_{ij})}{\ln(n)} \tag{15}$$

If $p_{ij} = 0$, then $p_{ij}\ln(p_{ij}) = 0$.

Step 4: We calculate the information utility value of each pollution index.

$$d_j = 1 - e_j \tag{16}$$

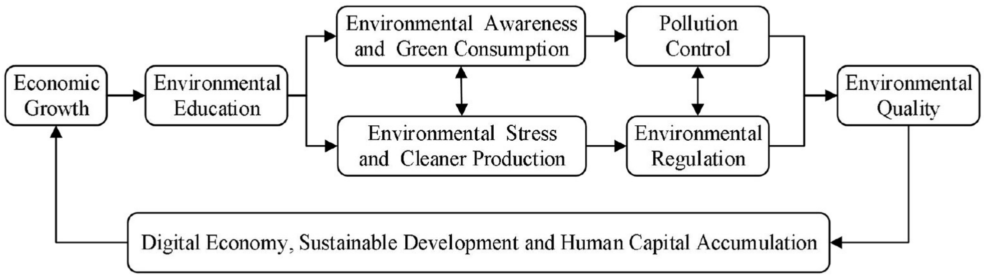

FIGURE 1
Economic growth and environmental sustainability.

Step 5: We calculate the weight of each pollution index.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad (17)$$

Step 6: We calculate the comprehensive pollution index.

$$pl_i = \sum_{j=1}^{m} w_j y_{ij} \quad (18)$$

Independent variables

Environmental education (*eedu*) is the core explanatory variable. Since environmental education is not listed in China's statistical data, we will use the fiscal expenditure for education as an alternative indicator of environmental education. The choice of proxy variable is based on two aspects. First, the Ministry of Education and the Ministry of Environmental Protection of the People's Republic of China jointly formulated the National Measures for the Application and Management of Social Practice Bases of Environmental Education in Primary and Secondary Schools, which is committed to standardizing the construction and management of social practice bases of environmental education in primary and secondary schools. Second, the Ministry of Education of the People's Republic of China issued the Notice on Implementing the Xi Jinping Thought of Ecological Civilization and Enhancing the Awareness of Ecological Environment in Primary and Secondary schools, requiring educational administrative departments at all levels and primary and secondary schools to reflect entirely thrives, green and low-carbon consumption in the teaching of relevant subjects, in-class and extra-curricular activities and all links of school management, so that students can effectively enhance awareness of the ecological environment. Improve the ability to protect the ecological environment. This means that all kinds of schools relying on fiscal education expenditure will carry environmental education through the whole education process; that is, education expenditure is an appropriate proxy variable for environmental education expenditure.

In the robustness test, we use the number of environmental publicity and education (*nedu*) as a substitute indicator of environmental education. In the theoretical analysis, we find that environmental education will affect the environmental pollution index through residential consumption and pollution control. So other independent variables are resident consumption (*rc*) and investment in pollution control (*pci*). The level of household consumption expresses resident consumption, and pollution control is measured by the amount of investment completed in industrial pollution control.

Other variables

Other variables conclude total population (*tp*), the proportion of the secondary industry (*psi*), amount of electricity consumption (*aec*), the degree of openness (*open*), and the fiscal and taxation capabilities (*ftc*). The global environmental change caused by humans has accelerated unprecedentedly, and the continued population growth has a particular relationship with environmental degradation (36). The upgrading of industrial structure accompanies economic growth, and the impact of industrial development on environmental quality is more obvious (37). At the same time, power consumption is an important manifestation of economic activity, and there have been studies using city lights to reflect economic development (38). It can be considered that secondary industry and power consumption are important factors affecting environmental quality. The division of labor and cooperation in international trade has brought environmental pollution problems, such as overseas investment in high-polluting industries (39). A country's tax revenue affects the ability to control pollution and the investment in environmental education. Therefore, when analyzing the impact of environmental quality, we consider a country's degree of openness and tax revenue.

Table 1 shows the definition of the variables. In the regression analysis, we take the logarithm of the variables (*eedu*, *nedu*, *rc*, *pci*, *tp*, and *aec*). The data in this article comes from the "China Statistical Yearbook" and "China Environmental Statistical Yearbook" from 2011 to 2017. Table 2 shows the statistical description of the variables.

Empirical model

Based on theoretical analysis and research hypotheses, the baseline model is set as follows:

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TABLE 1 Definition of the variables.

Variables			Description
Dependent variable	*pl*		Calculated from six pollution indicators using entropy method
	Secondary indicators	Nitrogen oxides	Nitrogen oxide emissions per unit of GDP
		Sulfur dioxide	Sulfur dioxide emissions per unit of GDP
		Industrial solid waste	Industrial solid waste discharged per unit of GDP
		Industrial wastewater	Wastewater discharged per unit of GDP
		Dust	Smoke and dust generated per unit of GDP
		Domestic garbage	Domestic waste generated per unit of GDP
Independent variables	*eedu*		Financial expenditure for education
	nedu		Number of environmental publicity and education
	rc		Resident consumption level
	pci		Complete investment in the treatment of industrial pollution
Other variables	*tp*		Total population
	psi		The proportion of the secondary industry
	aec		Amount of electricity consumption
	Open		Total import and export/GDP
	ftc		Tax revenue/GDP

TABLE 2 The statistical description of the variables.

Variables	Observations	Mean	Median	Max	Min
pl	217	0.191	0.151	0.720	0.017
eedu	217	6.396	6.475	7.854	4.354
nedu	155	5.593	5.505	8.731	2.890
rc	217	9.685	9.629	10.890	8.462
pci	217	2.682	2.856	4.953	−2.668
tp	217	8.122	8.244	9.404	5.733
psi	217	0.451	0.472	0.590	0.190
aec	217	7.176	7.252	8.693	3.168
Open	217	0.043	0.022	0.240	0.002
ftc	217	0.085	0.079	0.200	0.047

$$pl_{it} = \beta_0 + \beta_1 rc_{it} + \beta_2 pci_{it} + \beta_3 eedu_{it} + control + year + province + \varepsilon_{it} \quad (19)$$

$$pl_{it} = \beta_0 + \beta_1 rc_{it} + \beta_2 pci_{it} + \beta_3 eedu_{it} + \beta_4 eedu \times rc_{it} + control + year + province + \varepsilon_{it} \quad (20)$$

$$pl_{it} = \beta_0 + \beta_1 rc_{it} + \beta_2 pci_{it} + \beta_3 eedu_{it} + \beta_4 eedu \times pci_{it} + control + year + province + \varepsilon_{it} \quad (21)$$

Where i and t represent province and year, respectively. *pl* stands for pollution index, *rc* stands for household consumption, *pci* stands for pollution control investment, and *eedu* stands for environmental education investment. *control* contains other variables (*tp*, *psi*, *aec*, *open*, *ftc*). *year* represents the time effect of the province, and *province* represents the individual fixed effect of the province. ε denotes random disturbance terms.

Baseline regression results

Correlation coefficient test

The correlation coefficients between variables and their significance levels are shown in Table 3. Although the correlation between *pl* and *pci* is not statistically significant, *pl* is negatively correlated with *eedu*, *rc*, and *pci*. *eedu* has a significant positive correlation with *rc* and *pci*. Population, electricity consumption, economic openness, and tax revenue negatively correlate with the environmental pollution index. The development of the secondary industry has aggravated environmental pollution. Initially, the investment in environmental education is conducive to environmental quality, and residents' consumption and pollution control are also conducive to environmental quality. Environmental education positively impacts residents' consumption upgrades and pollution control. Environmental education may affect environmental quality through two channels, influencing residents'

TABLE 3 Correlation coefficients of variables.

	pl	*eedu*	*rc*	*pci*	*tp*	*psi*	*aec*	*open*	*ftc*
pl	1								
eedu	−0.521***	1							
rc	−0.518***	0.449***	1						
pci	−0.061	0.661***	0.338***	1					
tp	−0.346***	0.912***	0.179***	0.704***	1				
psi	0.324***	0.105	−0.318***	0.359***	0.299***	1			
aec	−0.094	0.808***	0.428***	0.855***	0.828***	0.343***	1		
Open	−0.437***	0.259***	0.658***	0.037	0.081	−0.352***	0.169**	1	
ftc	−0.184***	−0.087	0.507***	−0.196***	−0.302***	−0.627***	−0.170**	0.730**	1

(1) $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
(2) Standard errors are in parentheses.

consumption upgrade and pollution control. Of course, the conclusion is that the influence of other factors has not been considered. Next, we consider other influencing factors for further empirical verification.

Baseline regression results

Table 4 shows the baseline regression results. Model (1) shows that environmental education, household consumption levels, and pollution control significantly negatively impact the pollution index. The improvement of environmental education, the increase of residents' consumption level, and the increase of pollution control are all conducive to environmental quality. The result verifies *H1*.

Model (2) shows that the interaction between environmental education and residents' consumption level is positive ($eedu \times rc = 0.019$) but insignificant. It does not indicate that the impact of environmental education on environmental quality will decrease as the level of resident consumption increases. Meanwhile, the coefficients of environmental education, resident consumption, and pollution control are all significantly negative, indicating that the three have a promoting effect on improving environmental quality. The impact of environmental education and pollution control on environmental quality is consistent with the existing research conclusions. The reason resident consumption can improve environmental quality may be that with the deepening of environmental education, resident consumption pays more and more attention to green consumption (7), and green consumption can reduce the degree of environmental pollution (40). The conclusion verifies the *H2a*.

The influence coefficient of environmental education on environmental quality can also be verified by calculating the partial effect of environmental education. The calculation formula of the partial effect of environmental education incorporated into the resident consumption level is as follows: $\overline{eedu} = eedu + eedu \times \text{Mean}(rc)$. The results show that environmental education has a negative impact on the pollution index (−0.101); that is, environmental education investment has improved environmental quality. The conclusion still verifies the *H1*.

Model (3) shows that the interaction between environmental education and pollution control ($eedu \times pci$) is significantly negative. That is, with the increase of pollution control efforts, the impact of environmental education on environmental quality gradually increases. The conclusion verifies the *H2b*. It is worth noting that the coefficient of pollution control on environmental quality is significantly positive, which means that the investment in environmental control will increase the pollution level. The possible reason is that pollution control is relatively passive; that is, areas with more investment in pollution control often have more severe pollution. In Section 4.5 of this paper, quantile regression will be conducted according to the regional pollution degree to explore the reasons for this phenomenon further. In consideration of the coefficient value of *eedu* is not significantly negative. Similarly, we use Formula ($\overline{eedu} = eedu + eedu \times \text{Mean}(pci)$) to solve the partial effect of environmental education incorporating pollution control. The partial effect of environmental education ($\overline{eedu}$) is −0.071; environmental education investment improves environmental quality. The conclusion still verifies the *H1*. At the same time, this partial effect examines the main effect of environmental education and the interaction effect of pollution control and environmental control, so a smaller negative partial effect coefficient ($\overline{eedu} = -0.071$, $eedu = -0.044$) can also support *H2b*.

In addition, there is a significant negative correlation between the region's total population and the environmental pollution index. It can be seen that the larger the number of people, the more attention is paid to the environment, especially in large cities. Although the secondary industry positively correlates with the environmental pollution index, it is not statistically significant. However, there is a significant positive correlation between regional power consumption and the environmental pollution index, which to a certain extent, reflects that China's economic development has brought certain environmental pollution problems. There is a positive correlation between tax revenue and the environmental pollution index. The possible reason is that economic development sacrifices the environment, and tax revenue depends on economic growth. Increased taxation does not necessarily lead to a significant increase in investment in environmental pollution control. Table 4 shows a significant negative correlation between tax revenues and investment in environmental governance. Tax revenue has a negative correlation with environmental education.

TABLE 4 Baseline regression results.

Variables	(1)	(2)	(3)
eedu	−0.089***	−0.285*	−0.044
	(0.027)	(0.146)	(0.033)
rc	−0.233***	−0.348***	−0.246***
	(0.024)	(0.088)	(0.025)
pci	−0.016**	−0.018**	0.047*
	(0.008)	(0.008)	(0.028)
eedu × *rc*		0.019	
		(0.014)	
eedu × *pci*			−0.010**
			(0.004)
tp	−0.136***	−0.128***	−0.153***
	(0.023)	(0.024)	(0.024)
psi	0.060	0.068	0.057
	(0.085)	(0.085)	(0.084)
aec	0.217***	0.220***	0.213***
	(0.013)	(0.013)	(0.013)
Open	−0.664***	−0.737***	−0.559***
	(0.208)	(0.215)	(0.211)
ftc	1.427***	1.485***	1.275***
	(0.290)	(0.293)	(0.294)
Constant	2.490***	3.569***	2.509***
	(0.232)	(0.824)	(0.229)
Year fixed effect	YES	YES	YES
Province fixed effect	YES	YES	YES
N	217	217	217
Adjusted R^2	0.820	0.820	0.824
$\overline{eedu}$	−0.089	−0.101	−0.071

(1) $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
(2) Standard errors are in parentheses.

Robust regression results

Table 5 shows the robustness regression results of this article. We use *nedu* as the key independent variable. Model (4) shows that environmental education, residents' consumption level, and pollution control significantly negatively impact the pollution index. Environmental education, residents' consumption level, and pollution control are all conducive to environmental quality. The robustness test verifies *H1*.

In model (5), The inhibitory effect of environmental education on environmental pollution is significantly negative (−0.358), but the interaction between environmental education and residents' consumption level (*nedu* × *rc*) is significantly positive. It means that with the increase in residents' consumption, the inhibitory effect of environmental education on environmental pollution will gradually weaken. This makes it even more necessary to improve consumers' awareness of green consumption and achieve environmental protection through green consumption. The conclusion verifies the *H2a*. Consistent with the benchmark regression, the influence coefficient of environmental education on environmental quality can also be verified by calculating the partial effect of environmental education. The calculation formula of the partial effect of environmental education incorporated into residents' consumption level is as follows: $\overline{nedu} = nedu + nedu \times \text{Mean}(rc)$. The partial effect of environmental education impact ($\overline{nedu}$) is −0.009; that is, environmental education investment improves environmental quality. The robustness test verifies the *H1*.

TABLE 5 Robust regression results by replacing the key independent variable.

Variables	(4)	(5)	(6)
nedu	−0.015**	−0.358**	0.037**
	(0.006)	(0.158)	(0.016)
rc	−0.278***	−0.472***	−0.293***
	(0.032)	(0.094)	(0.031)
pci	−0.029***	−0.032***	0.082**
	(0.011)	(0.011)	(0.034)
nedu × *rc*		0.036**	
		(0.016)	
nedu × *pci*			−0.019***
			(0.006)
Constant	2.874***	4.709***	2.826***
	(0.289)	(0.888)	(0.279)
Control	YES	YES	YES
Year fixed effect	YES	YES	YES
Province fixed effect	YES	YES	YES
N	155	155	155
Adjusted R^2	0.827	0.832	0.840
$\overline{nedu}$	−0.015	−0.009	−0.014

(1) $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
(2) Standard errors are in parentheses.

In model (6), the interaction between environmental education and pollution control is considered, and it is found that *nedu* × *pci* is significantly negative. Still, the coefficient value of *nedu* is significantly positive, and the coefficient of *pci* is significantly positive. This shows that environmental education may affect the environmental level through pollution control investment. To some extent, this indicates that there is uncertainty in the direction of the effect of environmental education on environmental quality once the moderating effect of pollution control investment intensity is included. As the intensity of pollution control increases, the effect of environmental education on environmental quality shows a decreasing trend. This paradox will be solved by quantile regression. The coefficient of *nedu* is significantly positive; it is necessary to calculate the partial effect of environmental education, which is calculated as follows: $\overline{nedu} = nedu + nedu \times \text{Mean}(pci)$. The partial effect of environmental education impact ($\overline{nedu}$) is −0.014; that is, environmental education improves environmental quality. Robust regression results are

TABLE 6 Quantile regression results.

Variables	(7)	(8)	(9)	(10)	(11)
eedu	−0.076***	−0.096***	−0.097***	−0.129***	−0.078***
	(0.013)	(0.022)	(0.023)	(0.028)	(0.027)
rc	−0.170***	−0.209***	−0.225***	−0.202***	−0.274***
	(0.012)	(0.020)	(0.025)	(0.026)	(0.025)
pci	−0.022***	−0.020***	−0.014*	−0.006	−0.004
	(0.004)	(0.006)	(0.008)	(0.008)	(0.008)
Control	YES	YES	YES	YES	YES
Quantile	0.10	0.35	0.50	0.65	0.90

(1) $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.
(2) Standard errors are in parentheses.

consistent with baseline regression results. The robustness test verifies *H1*.

Quantile regression results

To further analyze the results of model (3) and model (6) and verify the impact of pollution control on the environmental pollution index, we conducted quantile regression analysis according to the size of the pollution control investment. Table 6 shows environmental education and residents' consumption level significantly negatively impact the pollution index; that is, environmental education and residents' consumption level are all conducive to environmental quality. Moreover, from the quantile regression coefficient, the reduction of the pollution index is more dependent on environmental education and residents' green consumption tendency.

It is worth noting that with the improvement of the region's pollution index, the pollution control role is getting smaller and smaller. The possible reason is that the increase in investment in pollution control is a passive choice. First, in areas with severe pollution, investment in pollution control has to be increased to meet the environmental protection requirements of the central government. Second, improving residents' environmental awareness will also encourage government departments to increase investment in environmental governance. Residents' emphasis on the ecological environment and protests against polluting companies or behaviors have forced local governments to increase their control of environmental pollution (41). Quantile regression results verify the *H3*.

Conclusions and discussions

Conclusions

The low-carbon economy is the dominant choice for human society to solve the dilemma of environmental governance. The high-quality natural environment provides a good production and consumption atmosphere for economic growth. This paper's theoretical and empirical research can provide the following four conclusions. First, environmental education will significantly reduce the environmental pollution index, which can be supported by the benchmark regression coefficient of environmental education and its partial effect coefficient.

Second, from the perspective of green consumption and cleaner production channels, with the improvement of residents' consumption level, the promotion effect of environmental education on the progress of environmental quality shows a downward trend, so it is more necessary to truly enhance residents' awareness of green consumption through environmental education. It will also push companies toward cleaner production through technological innovation and environmental investment.

Third, from the perspective of pollution control channels, pollution control investment cannot effectively promote environmental quality because there is a paradox of positive correlation between regional pollution degree and pollution investment amount. In areas with higher pollution degrees, more pollution control costs need to be invested in meeting environmental protection standards or residents' willingness to protect environmental protection. The conclusion of quantile regression verifies this phenomenon.

In addition, we find that there is uncertainty about pollution control in improving environmental quality. With the improvement of the pollution index of the region itself, the role of pollution control is getting smaller and smaller. This indicates that the environmental governance issues in areas with higher pollution levels are more passive. It also means that environmental education should be carried out first to avoid passive responses when environmental pollution is severe.

Managerial implications

First of all, it is necessary to form a consensus on environmental protection in the whole society through environmental education from a strategic perspective. Chinese local governments should respond to the unified deployment of the CPC Central Committee and the State Council of the People's Republic of China, distinguish between different objects such as state organs, enterprises, public institutions, social organizations, schools, families, and the public, and penetrate environmental education into family education, primary education, higher education, vocational education, cadre education, and training and other links. Environmental education should penetrate all stages of citizens' lives according to its purpose and tasks, combined with its universality and life-long characteristics. This is an important measure to implement the concept that clear waters and lush mountains are gold and silver mountains and also a necessary choice for a low-carbon economy and sustainable development.

Secondly, from the perspective of the channel mechanism of environmental education. Environmental education should emphasize its role in promoting citizens' environmental awareness and reflect the positive role of environmental education in promoting residents' green consumption and enterprises' green production. At the same time, local environmental protection and environmental education departments should actively respond to hot environmental issues concerned by the people with a scientific and pragmatic attitude, guide the public to participate in environmental protection work in a mature, rational, orderly, and effective manner, gather the people's hearts, wisdom and strength to the greatest extent, and jointly promote the steady improvement of environmental quality.

Finally, environmental education legislation should be accelerated from the perspective of legal regulation. Currently, the connection between environmental education and legislation in China exists only in single words and sentences of individual legal provisions. For example, the Environmental Protection Law only stipulates the principles of environmental education. According to the Environmental Protection Law of the People's Republic of China, the Education Law of the People's Republic of China and other laws and regulations, Jiangsu Province has formulated the Measures for the Promotion of Ecological Civilization Education of Jiangsu Province, which also defines the scope and implementation subjects of ecological civilization education in schools, families, and society. However, it is still only an administrative document of the local government. It has not yet risen to the level of the legal system. In fact, environmental education legislation can regulate the behavior of citizens and enterprises and provide a legal system guarantee for the government's environmental education and environmental governance.

Theoretical contributions and research limitations

There are two marginal contributions in this paper. Firstly, this paper improves the Ramsey model and finds that the fit between consumption structure and industrial structure is an important factor for environmental education to improve environmental quality, which provides a factual basis for environmental protection practice. Secondly, this paper conducts theoretical analysis and empirical tests on the transmission mechanism of environmental education to environmental quality and finds that environmental education can improve environmental quality through pollution control and green consumption, especially for heavily polluted areas. Environmental protection and environmental education should be strengthened, especially for heavily polluted areas, which is an expansion of the research on the transmission mechanism of environmental education.

There are a few shortcomings in this paper. For example, due to data availability, this paper uses the data at the provincial level in China and does not analyze the city and county levels. This paper also fails to explore how environmental education affects citizens' environmental awareness and, thus, environmental quality. It does not explore the influencing mechanism of environmental education on high-quality economic and social development, which are future research directions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW, JW, and WY conceived the study and drafted the manuscript. YW designed the model. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Spatial network and driving factors of low-carbon patent applications in China from a public health perspective

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Introduction: The natural disasters and climate anomalies caused by increasing global carbon emissions have seriously threatened public health. To solve increasingly serious environmental pollution problems, the Chinese government has committed itself to achieving the goals of peak carbon emissions and carbon neutrality. The low-carbon patent application is an important means to achieve these goals and promote public health.

Methods: This study analyzes the basic situation, spatial network, and influencing factors of low-carbon patent applications in China since 2001 at the provincial and urban agglomeration levels using social network analysis based on data from the Incopat global patent database.

Results: The following findings are established. (1) From the number of low-carbon patent applications, the total number of low-carbon patent applications in China increased year by year, while the number of applications in the eastern region was larger than those in the central and western regions, but such regional differences had been decreasing. (2) At the interprovincial level, low-carbon patent applications showed a complex and multithreaded network structure. In particular, the eastern coastal provinces occupied the core position in the network. The weighted degree distribution of China's interprovincial low-carbon patent cooperation network is affected by various factors, including economic development, financial support, local scientific research level, and low-carbon awareness. (3) At the urban agglomeration level, the eastern coastal urban agglomerations showed a radial structure with the central city as the core. Urban innovation capability, economic development, low-carbon development awareness, level of technology import from overseas, and informatization level are highly correlated with the weighted degree of low-carbon cooperation networks of urban agglomerations.

Discussion: This study provides ideas for the construction and governance of low-carbon technology innovation system and perspectives for theoretical research on public health and high-quality development in China.

KEYWORDS

public health, low-carbon patent application, social network, spatial correlation structure, urban agglomeration

1. Introduction

Climate warming has become a global concern. Countries around the world have taken measures to address this issue, including successively signing three international laws, namely, the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement, to establish a global climate governance system (1). The Chinese government attaches great importance to this issue and has committed itself to achieving the goals of peak carbon emissions and carbon neutrality by 2030 and 2060, respectively (2, 3). Low-carbon technology is an important way to achieve these goals. Low-carbon patents are an innovative form of low-carbon technology and enable accurate measurement of the research situation of low-carbon technology in various regions (4). Since the development of low-carbon innovation in various regions of China is strongly influenced by regional economic and other factors, it leads to spatial heterogeneity in low-carbon technology innovation, which poses a challenge to the formation of cross-regional cooperation networks. Therefore, it is necessary to analyze the overall network structure and evolution of low-carbon collaborative innovation and identify the key roles of different regions in the network, as well as the influencing factors affecting regional low-carbon technologies, in order to improve the regional collaboration of low-carbon innovation, find influential partners for local governments' low-carbon innovation activities, and provide objective references for public health policy formulation (5).

In recent years, patent cooperation networks have become a popular Research Topic, in which the analysis of data related to patent information, joint patent applications, and collaborative papers are the main data sources for technological innovation activities (6–8). Numerous studies have been undertaken on patent cooperation networks in terms of different disciplines and perspectives using social network analysis and other methods based on data from world-renowned patent databases, such as the databases of the USPTO and the EPO and the Incopat database. For example, the formation, evolution, structure, and characteristics of patent cooperation networks in industries such as solar cells (9, 10), nanotechnology (11, 12), and measurement and chemistry (13) were investigated by analyzing centrality, structural holes, network density, and other indicators (14–19).

In recent years, the formation mechanism of the spatial network of patent applications has begun to receive considerable attention. It has been reported that geographic distance, technological relevance, small-world effects, social proximity, and cooperative relationships all have an impact on network formation (20–24). A literature review reveals that the spatial network of patent applications has rarely been investigated from the perspective of regions and urban agglomerations, and it is even rarer to focus on low-carbon patents. Moreover, previous studies only focus on a single level, such as country, province, urban agglomeration, urban area, or rural area (25–28). Few studies have comprehensively examined the spatial network of low-carbon patent applications and the influencing factors from the perspective of regions, provinces, and urban agglomerations.

At present, China is in a critical period of low-carbon transformation (29). In addition, it may be difficult to control the global impact of the COVID-19 pandemic in a short period of time. Therefore, it is worth considering how to achieve the goals of peak carbon emissions and carbon neutrality in an orderly manner in the post-pandemic period. To this end, this study aims to investigate the spatial characteristics of low-carbon technologies in China at the levels of urban agglomerations, regions, and provinces using low-carbon patent cooperation data to identify problems from a new perspective and help clarify the current technology accumulation in this field in China. On this basis, strategies to optimize the low-carbon patent cooperation network in the post-pandemic period are proposed to provide patent information support for scientific work in the low-carbon field and to provide a theoretical basis for patented technology development strategies.

This study provides the following marginal contributions. First, this study expands the theoretical system of the geography of innovation in a vertical three-dimensional way through social network analysis. Second, this study analyzes the innovation functions and roles of cities in the networks of urban agglomerations, regions, and provinces, strengthening the theoretical research of urban geography. Third, the conclusions may provide a strategic basis for the government and related functional departments to innovate and develop low-carbon technologies.

The remainder of the paper is structured as follows: Section 2 describes the data and methodology. Section 3 analyzes the spatiotemporal evolution of low-carbon patent applications in China at the national level. Sections 4 and 5 analyze the spatial structure of the patent network and the driving factors at the provincial level. Sections 6 and 7 present a discussion at the level of urban agglomerations. Section 8 presents the conclusions, implications, potential contributions, and limitations.

2. Data and methodology

2.1. Subjects

This study covers 31 provinces/municipalities in three regions of China (except Hong Kong, Macau, and Taiwan) and five major urban agglomerations along the eastern coast (Table 1) (30).

2.2. Methods and data

2.2.1. Data

In 2013, the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) jointly launched the CPC-Y02 patent classification system for technologies or applications for mitigation or adaptation against climate change. Due to the structural and systemic advantages of this system, it has been extensively used in the research of low-carbon patent-related issues in recent years (31, 32).

Low-carbon patent application data are from the Incopat global patent database. Specifically, patents in the CPC-Y02 class were retrieved from the Incopat database on August 26, 2022.

TABLE 1 Description of the correspondence of the study subjects.

Region	Province	Urban agglomeration	City
East	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan	Beijing-Tianjin-Hebei (BTH) region	Baoding, Beijing, Cangzhou, Chengde, Langfang, Qinhuangdao, Shijiazhuang, Tangshan, Tianjin, Zhangjiakou
Central	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan	Pearl River Delta (PRD)	Guangzhou, Shenzhen, Foshan, Dongguan, Zhaoqing, Jiangmen, Zhuhai, Huizhou, Zhongshan
West	Sichuan, Chongqing, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Guangxi, Inner Mongolia	Yangtze River Delta (YRD)	Changzhou, Hangzhou, Huzhou, Jiaxing, Nanjing, Nantong, Ningbo, Shanghai, Shaoxing, Suzhou, Taizhou, Taizhou, Wuxi, Yangzhou, Zhenjiang, Zhoushan
		Shandong Peninsula (SP)	Binzhou, Dezhou, Dongying, Jinan, Liaocheng, Qingdao, Rizhao, Tai'an, Weihai, Weifang, Yantai, Zibo
		Western Taiwan Straits (WTS) Economic Zone	Chaozhou, Fuzhou, Ningde, Putian, Quanzhou, Xiamen, Shantou, Zhangzhou, Wenzhou, Jieyang, Shanwei

2.2.2. Methods

Social network analysis is a quantitative analysis method developed from mathematical methods and graph theory and in recent years has become one of the most widely used methods in sociology and economics (33). This study uses social network analysis and related theories to analyze the structural characteristics, network pattern evolution, and driving factors of China's low-carbon patent application network. The indicators involved in this study are as follows.

Centrality: This measures the node control in the entire factor network and is defined as follows:

$$C_D(n_i) = d(n_i) = \sum_j X_{ij} = \sum_i X_{ji}, C'_D(n_i) = \frac{d(n_i)}{g-1} \quad (1)$$

Where $C_D(n_i)$ is the absolute centrality of node i; X_{ij} is 0 or 1, indicating whether nodes j and i are related or not; and g is the number of network nodes.

Closeness centrality measures how close a node is to all other nodes, reflecting its control over other nodes.

$$CC_i = \frac{g-1}{\sum_{j=1,j\neq i}^{N} d_{ij}} \quad (2)$$

Where d_{ij} is the number of steps in the shortest path between nodes i and j.

Betweenness centrality measures the degree to which a node is located at the center of other nodes, thus reflecting a state's ability to control the channels and mediate the flow of energy in the network. Assuming that the number of shortest paths between nodes j and k is g_{jk} and the number of shortest paths between nodes j and k passing through node i is $g_{jk}(i)$, the ability of node i to control the association between nodes j and k can be defined as $b_{jk} = \frac{g_{jk}(i)}{g_{jk}}$.

$$BC_i = \frac{2\sum_j^n \sum_k^n b_{jk}(i)}{N^2 - 3N + 2}, \text{ where } j \neq k \neq i \text{ and } j < k \quad (3)$$

Weighted degree: This measures the weight of low-carbon patent cooperation that occurs at a node. A higher weighted degree value means a higher weight of low-carbon patent cooperation at the node. The weighted degree can be divided into weighted in-degree and out-degree. It is calculated as follows:

$$C_w(i) = \sum_{j=1}^{N} W_{ij} + \sum_{j=1}^{N} W_{ji} \quad (4)$$

Where $C_w(i)$, $\sum_{j=1}^{N} W_{ij}$, and $\sum_{j=1}^{N} W_{ji}$ are the weighted degree, weighted out-degree, and weighted in-degree of node i, respectively.

GeoDetector: GeoDetector is a spatial analysis model used to assess the relationship between a geographical attribute and its explanatory factors. It is widely used to investigate the influencing factors of natural and socioeconomic phenomena. GeoDetector requires only a few preconditions and has obvious advantages when dealing with mixed-type data. The factor detector in GeoDetector was used to assess the explanatory power of each influencing factor and its changes in the centrality of China's interprovincial low-carbon patent cooperation network (34). The factor detector is expressed as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} \sigma_h^2 N_h}{N\sigma^2} \quad (5)$$

Where q is the detection capability of an influencing factor for the centrality of China's interprovincial low-carbon patent cooperation network; $h = 1\ldots$; L is the classification of each factor of the variable; σ^2 is the total variance of the centrality of the interprovincial low-carbon patent cooperation network; σ_h^2 is the variance of the interprovincial low-carbon patent cooperation network; N is the number of provinces in China; and Nh is the number of types of influencing Factor X. The value range of q is (0, 1). The larger q is, the greater the influence of this factor on interprovincial low-carbon patent cooperation.

Correlation coefficient: This measures how closely two phenomena (elements) are correlated. Due to factors such as network capital, there are differences in the number of low-carbon patent applications in different provinces and cities. The relationship of the number of low-carbon patent applications with the effective size, constraint, closeness, betweenness, and weighted degree of the province was examined by linear correlation analysis. The correlation coefficient is calculated as follows:

$$\gamma = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{(x-\bar{x})^2 (y-\bar{y})^2}} \quad (6)$$

Where γ is the correlation coefficient; x and y are two sets of variables; and $\bar{x}$ *and* $\bar{y}$ are the means of the variables. The value of γ is between −1 and 1. $\gamma > 0$ indicates a positive correlation, and $\gamma < 0$ indicates a negative correlation. The larger the absolute value of γ is, the greater the correlation.

Low-carbon search index: The low-carbon search indices of prefecture-level cities or provinces from January 1 to December 31, 2021, were collected from the Baidu Index website using the keyword "low-carbon" to reflect online attention to the low-carbon field.

Block model: The block model is a method of analyzing the node location in a network (35, 36). Wasserman and Faust (37) created a method for evaluating the relationship between positions within a network. According to the classifications of previous studies, four blocks are defined according to position: bidirectional spillover, main benefit, broker, and main spillover blocks (38).

GRA: This analysis is based on gray system theory. The parent sequence is the centrality of the urban low-carbon patent cooperation network (39). The subsequences are the number of patent applications, per capita GDP, low-carbon search index, total volume of post and telecommunications business, and actually utilized value of foreign direct investment, representing 5 influencing factors. The correlation coefficients were calculated by non-dimensionalizing the original data. DPS software was used for data processing and analysis to reduce the difficulties caused by complex modeling and the large amount of data (40, 41).

3. Spatiotemporal evolution of low-carbon patent applications

3.1. Number of low-carbon patent applications

As shown in Figure 1, the number of China's low-carbon patent applications increased year by year until 2021, when it decreased due to the COVID-19 pandemic. At the regional level, the number of applications in the eastern region was much higher than that in the central and western regions combined. The number of patent applications in the eastern region as a percentage of the national total increased from 85.09% in 2001 to 89.03% in 2006 and then decreased to 70.83% in 2021. The number of patent applications in the central and western regions as a percentage of the national total decreased from 6.83 and 8.07% in 2001 to 5.15 and 5.82% in 2006 and then increased to 13.41 and 15.76% in 2021, respectively.

3.2. Spatial differences in low-carbon patent applications

As shown in Table 2, there are obvious regional differences in the number of low-carbon patent applications in China. Overall, the differences in the number of low-carbon patent applications both within and between the three regions continued to decrease. The interprovincial Gini coefficient decreased from 0.9333 in 2001 to 0.5791 in 2021, indicating a decreasing difference in the number of low-carbon patent applications between provinces. At the regional level, the Gini coefficient within the eastern region continued to decrease, indicating a decreasing internal difference. The Gini coefficients within the central and western regions increased and then decreased, peaking in 2006 and 2011, respectively.

3.3. Spatial trends of low-carbon patent applications in provinces

As shown in Figure 2, two characteristics are present in the number of low-carbon patent applications in China's 31 provinces/municipalities due to local economic development, scientific research, and policies. First, there were great changes in the number of low-carbon patent applications. Most provinces/municipalities showed changes in both the number of low-carbon patent applications and the ranking. In particular, Beijing was always ranked first in the number of low-carbon patent applications. Jiangsu rose from fourth in 2001 to second in 2021. Guangdong was always ranked in the top three. Fujian, Beijing, Guangxi, and Hunan showed small changes in the ranking by the number of low-carbon applications. Shandong, Tianjin, Jiangsu, Zhejiang, Hubei, Anhui, Qinghai, Henan, Jiangxi, Shaanxi, and Hebei rose in rankings, while the rest of the provinces dropped. Second, the number of low-carbon patent applications varied significantly between provinces. For example, the number of low-carbon patent applications in Beijing, Jiangsu, Guangdong, Zhejiang, and Shandong exceeded 1,000 in 2021, whereas it was <500 in Heilongjiang, Jilin, and Liaoning in Northeast China.

4. Evolution of the low-carbon patent application spatial network at the province level

4.1. General network characteristics

The overall network characteristics were measured using Gephi and Ucinet. First, the overall network density was increased, as shown in Table 3. The network density increased from 0.133 in 2001 to 0.847 in 2021, indicating that China has formed an effective low-carbon cooperation network as a whole. There are obvious spillover correlations of patent cooperation among all provinces, and the degree of such cooperation is increasing. Second, the evolution trend of the average shortest path length and the clustering coefficient showed increasing clustering of China's low-carbon patent cooperation network. The average path length of

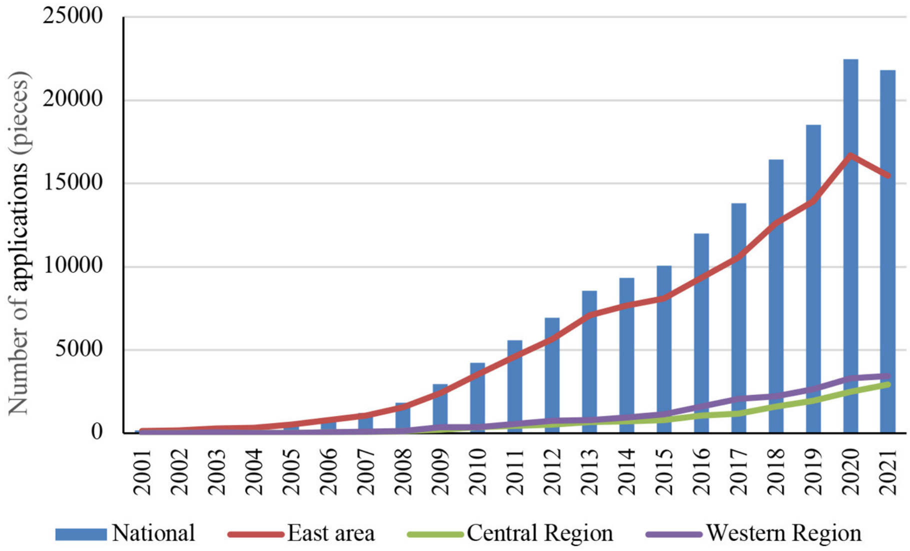

FIGURE 1
Number of low-carbon patent applications nationwide and in the eastern, central, and western regions.

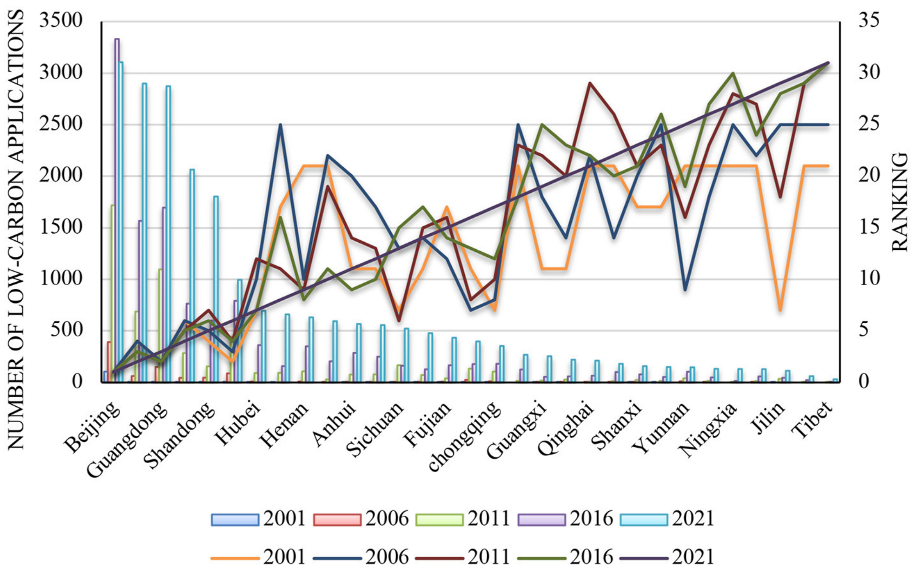

FIGURE 2
Number and ranking of low-carbon patent applications of the 31 provinces/municipalities.

TABLE 2 The Gini coefficients of low-carbon patent applications nationwide and in the eastern, central, and western regions.

Year	Gini coefficient	Intraregional difference		
		East	West	Central
2001	0.9333	0.8390	0.4722	0.1481
2006	0.8853	0.6944	0.3864	0.6296
2011	0.8219	0.5645	0.6452	0.1774
2016	0.7999	0.5390	0.2313	0.1240
2021	0.5791	0.1051	0.2623	0.0118

TABLE 3 Overall characteristics of China's low-carbon patent cooperation network.

Year	Number of nodes	Number of edges	Network density	Average clustering coefficient	Average path length	Average degree
2001	21	28	0.133	0.702	1.965	2.667
2006	26	53	0.163	0.479	2.138	4.077
2011	31	169	0.363	0.663	1.699	10.903
2016	31	278	0.598	0.746	1.402	17.935
2021	31	394	0.847	0.890	1.153	25.419

TABLE 4 Top 10 provinces/municipalities in China's low-carbon cooperation network in terms of weighted degree in 2001–2021.

2001	Weighted degree	2011	Weighted degree	2021	Weighted degree
Beijing	77	Beijing	2,025	Beijing	10,051
Shanghai	56	Shanghai	925	Jiangsu	5,068
Guangdong	21	Guangdong	894	Guangdong	4,361
Shanxi	16	Jiangsu	681	Zhejiang	2,464
Hubei	7	Liaoning	408	Shanghai	2,243
Shandong	7	Tianjin	355	Shandong	1,861
Jiangsu	5	Zhejiang	290	Hebei	1,773
Liaoning	4	Fujian	286	Tianjin	1,614
Zhejiang	4	Henan	208	Hunan	1,598
Anhui	3	Hebei	178	Shaanxi	1,360

the network shows an upward and then downward trend over time, with a mean value of 1.671. Third, as revealed by the time series, the average degree increased from 2.667 in 2001 to 25.419 in 2021, showing an overall increase. This indicates that the provinces have an increasing influence on China's low-carbon patent cooperation network.

4.2. Individual network characteristics

The weighted degree reflects the status of each province in China's low-carbon patent cooperation network to some extent. As shown in Table 4, the weighted degrees of Beijing, Shanghai, Guangdong, Jiangsu, Zhejiang, and Tianjin along the eastern coast were ranked among the top 10 in 2001. In 2011, the network pattern changed. Specifically, Shanxi, Hubei, Shandong, Anhui, and Sichuan dropped out of the top ten, whereas Fujian, Henan, and Hebei had increased weighted degrees and broke into the top ten nationwide. In 2021, Shanghai dropped from second to fifth due to the COVID-19 pandemic. Meanwhile, Jiangsu broke into the top three, Liaoning, Fujian and Henan dropped out of the top 10, and Shandong returned to the top ten.

Betweenness centrality reflects the shortest cooperation path between provinces in China's low-carbon patent cooperation network. The higher it is, the greater the control of the province. As shown in Table 5, Beijing, Shanghai, Guangdong, Jiangsu, and Hubei ranked high in terms of betweenness centrality from 2001 to 2020, indicating that these provinces/municipalities are at the core of China's low-carbon patent cooperation network.

Closeness centrality reflects the sum of low-carbon patent cooperation distances between provinces. The higher it is, the closer the province is to other provinces in the low-carbon patent cooperation network. Closeness centrality also indicates the degree of independence of nodes. In 2001, Hunan, Chongqing, Beijing, Guangdong, Shanghai, Shanxi, Hubei, Sichuan, Jiangsu, and Shandong ranked high in terms of closeness centrality, as shown in Table 5. Except for Shaanxi, Zhejiang, and Anhui, the top 10 provinces in 2021 are the same as those in 2001.

4.3. Segmentation of the low-carbon patent cooperation network

The low-carbon patent cooperation network is segmented using the CONCOR block model method to investigate the spatial clustering of provincial patent cooperation in China. Specifically, the maximum segmentation density is set to 2, and the convergence criterion is 0.2. The Chinese low-carbon patent cooperation network in 2021 is divided into bidirectional spillover, main benefit, and broker blocks through two iterations. The segmentation results are shown in Table 6. The provinces included in each block are shown in Table 7.

In terms of the composition of block members, Block 1 received and sent 208 and 206 relations in 2021, respectively. The proportion of expected internal relations (26.67%) is smaller

TABLE 5 Top 10 provinces/municipalities in China's low-carbon cooperation network in terms of betweenness and closeness centrality in 2001–2021.

2001	Betweenness	2011	Betweenness	2021	Betweenness	2001	Closeness	2011	Closeness	2021	Closeness
Beijing	127.333	Beijing	59.143	Beijing	4.214	Hunan	1.000	Beijing	0.882	Beijing	1.000
Guangdong	28.833	Shanghai	39.889	Guangdong	4.214	Chongqing	1.000	Shanghai	0.811	Jiangsu	1.000
Hubei	5.667	Jiangsu	38.026	Hubei	4.214	Beijing	0.900	Jiangsu	0.811	Guangdong	1.000
Shanghai	1.833	Shaanxi	30.520	Jiangsu	4.214	Guangdong	0.621	Guangdong	0.750	Shanghai	1.000
Shanxi	1.833	Liaoning	25.014	Shaanxi	4.214	Shanghai	0.563	Liaoning	0.667	Shaanxi	1.000
Jiangsu	0.500	Sichuan	18.824	Shanghai	4.214	Shanxi	0.563	Zhejiang	0.667	Hubei	1.000
Anhui	0.000	Guangdong	18.456	Chongqing	3.944	Hubei	0.545	Henan	0.667	Zhejiang	0.968
Gansu	0.000	Henan	13.831	Sichuan	3.607	Sichuan	0.529	Hunan	0.667	Shandong	0.968
Hebei	0.000	Zhejiang	13.767	Shandong	3.602	Jiangsu	0.514	Shaanxi	0.667	Sichuan	0.968
Jiangxi	0.000	Hubei	12.936	Tianjin	3.559	Shandong	0.500	Sichuan	0.652	Anhui	0.968

TABLE 6 Segmentation of China's low-carbon patent cooperation network in 2021.

2021	Number of members	Number of relations received			Number of relations sent			Proportion of expected internal relations (%)	Proportion of actual internal relations (%)	Block
		Inside the block	Outside the block	Total	Inside the block	Outside the block	Total			
Block 1	9	60	148	208	60	146	206	26.67	29.13	Main benefit block
Block 2	17	183	170	353	183	173	356	53.33	51.40	Bidirectional spillover block
Block 3	3	6	81	87	6	80	86	6.67	3.49	Broker block
Block 4	2	2	30	32	2	30	32	3.33	6.25	Main benefit block

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TABLE 7 Provinces/municipalities in each block of China's low-carbon patent cooperation network in 2021.

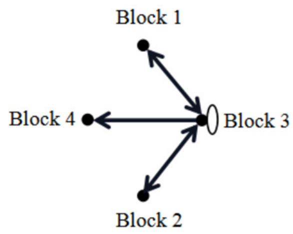
Block	Provinces/municipalities
Block 1	Anhui, Jiangxi, Fujian, Tianjin, Hubei, Hunan, Tibet, Jiangsu, and Zhejiang
Block 2	Guizhou, Gansu, Qinghai, Henan, Jilin, Shaanxi, Liaoning, Chongqing, Inner Mongolia, Ningxia, Shandong, Xinjiang, Shanxi, Hebei, Sichuan, Heilongjiang, and Yunnan
Block 3	Beijing, Guangdong, and Shanghai
Block 4	Hainan and Guangxi

than that of the actual internal relations (29.13%). A total of 32 relations were received and sent by Block 4. The proportion of expected internal relations (3.33%) is smaller than that of actual internal relations (6.25%). Thus, these two blocks are both main benefit blocks. They are largely driven by patent cooperation in other provinces. Block 3, including Beijing, Guangdong, and Shanghai, received and sent a total of 87 and 86 relations, respectively. The proportion of expected internal relations (6.67%) is larger than that of actual internal relations (3.49%). Hence, it is a broker block. This block has played an important role in driving the low-carbon patent cooperation of other blocks. Block 2, represented by Chongqing, Shandong, and Sichuan, received and sent a total of 353 and 356 relations, respectively. The proportion of expected internal relations (53.33%) is larger than that of actual internal relations (51.40%). Hence, it is a bidirectional spillover block. Provinces within this block have strong low-carbon patent cooperation, which not only has a spatial spillover effect on other provinces inside the block but also drives the low-carbon patent cooperation of provinces outside the block.

In addition, an image matrix is generated using the density criterion to describe the relationship between the blocks. The values in the density matrix for each year that are greater than the overall network density are replaced with 1, and those smaller than the overall network density are replaced with 0. In this way, the relationship between the blocks at each stage and the image matrix are obtained, as shown in Figure 3. In 2021, the strongest internal relations were observed in Block 3. In addition to close patent cooperation between its members, Block 3 sent and received a large number of relations to and from Blocks 1 and 2. Except for receiving relations from Block 3, Block 4 rarely sent and received relations to and from other blocks. Relations within Block 4 were also scarce. There is a clubbing effect between the blocks. Therefore, block members with sparse relations should focus on strengthening patent cooperation with external core block members to avoid being "outliers" to ensure their position in the low-carbon patent cooperation network.

4.4. Core-periphery structure in a low-carbon patent cooperation network

The coreness of each province was calculated using Ucinet. Provinces with coreness values >0.2 were included in the core area. The distribution of provinces in the core area is shown in Table 8. From 2001 to 2021, Beijing held the top spot in China's low-carbon patent cooperation network in terms of coreness. Jiangsu has jumped from the semiperipheral area to the core area since 2016. Henan and Zhejiang were among the core provinces in 2016 but were replaced by Guangdong and Hebei in 2021.



Block	1	2	3	4
1	0	0	1	0
2	0	0	1	0
3	1	1	1	1
4	0	0	0	0

FIGURE 3
Relationship between the blocks of China's low-carbon cooperation network in 2021 and the image matrix.

TABLE 8 Core provinces in China's low-carbon patent cooperation network each year.

Year	Core province
2001	Beijing
2006	Beijing
2011	Beijing
2016	Beijing, Jiangsu, Henan, and Zhejiang
2021	Beijing, Guangdong, Hebei, and Jiangsu

4.5. Interregional relations in a low-carbon patent cooperation network

China was divided into eastern, central, and western regions to calculate the basic statistical characteristics of the network using Gephi. As seen from Table 9, the interregional low-carbon patent cooperation network improved significantly over time. The number of east-central, east-west, and central-west nodes increased from 10, 8, and 2 in 2001 to 19, 22, and 21 in 2021, respectively, and the number of edges increased from 10, 7, and 1 in 2001 to 84, 103, and 78 in 2021, respectively. In terms of network connectivity, the average degree increased from 2, 1.75, and 1 in 2001 to 8.842, 9.364, and 7.429 in 2021, respectively, and the average weighted degree increased from 6.2, 3, and 2 in 2001 to 474, 363.091, and 75.143 in 2021, respectively. At the intraregional level, the number of east-east, central-central, and west-west nodes increased from 8, 0, and 0 in 2001 to 10, 9, and 12 in 2021, respectively, and the number of edges increased from 10, 0, and

0 in 2001 to 45, 32, and 52 in 2021, respectively. In terms of network connectivity, the average degree increased from 2.5, 0, and 0 in 2001 to 9, 7.111, and 8.667 in 2021, respectively, and the average weighted degree increased from 16.5, 0, and 0 in 2001 to 2015.6, 83.778, and 115.333 in 2021, respectively. Overall, the interregional low-carbon patent cooperation network is not only more closely connected but also has stronger connection strength than the intraregional interprovincial cooperation network, except for east-east cooperation.

5. Influencing factors of interprovincial low-carbon patent cooperation network

5.1. Selection of influencing factors

The correlation coefficients between the weighted degree of China's interprovincial low-carbon patent cooperation network and the influencing factors were calculated with the weighted degree of the network in 2021 as the dependent variable and GDP per capita, per capita disposable income of residents, and the value added of the secondary and tertiary industries as a percentage of GDP as independent variables. The data are from the China Statistical Yearbook.

5.2. Results of influencing factors

The results of the influencing factors are shown in Table 10. Nine influencing factors have a significant impact on the establishment of China's interprovincial low-carbon patent cooperation network. This indicates that the weighted degree distribution of China's interprovincial low-carbon patent cooperation network is affected by various factors, such as economic development, financial support, local scientific research level, and local awareness. The explanatory power of each influencing factor is between 40 and 70%. They can be divided into primary and secondary influencing factors according to the explanatory power. The primary influencing factors include the R&D expenditure of industrial enterprises above a designated size, the number of effective R&D invention patents of industrial enterprises above a designated size, and the low-carbon search index. The secondary influencing factors include per capita GDP, per capita disposable income of residents, value added of the secondary and tertiary industries as a percentage of GDP, local government fiscal expenditure as a percentage of GDP, science and technology expenditure as a percentage of local government fiscal expenditure, and the number of undergraduates and college students.

5.2.1. Quality of economic development

The regression results showed a significant correlation with per capita GDP, per capita disposable income of residents, and value added of the secondary and tertiary industries as a percentage of GDP. This suggests that provinces with a reasonable provincial economic structure and high level of economic development can agglomerate to attract innovative elements and, thus, form a closer connection with other provinces for low-carbon patent innovation.

5.2.2. Financial support

The regression results showed a significant correlation at the 10% level with local government fiscal expenditure as a percentage of GDP and science and technology expenditure as a percentage of local government fiscal expenditure. Moreover, a higher correlation was observed with science and technology expenditure as a percentage of local government fiscal expenditure, indicating that this factor plays the largest role in local financial support.

5.2.3. Local scientific research level

The importance of science and technology is self-evident (42). Provinces with higher research capabilities have higher levels of low-carbon patent development. The R&D expenditures of industrial enterprises above a designated size and the number of effective R&D invention patents of industrial enterprises above a designated size ranked first and third, respectively, among all factors with significant correlations. This indicates that the local scientific research level has an important influence on the weighted degree of the low-carbon patent cooperation network.

5.2.4. Local environmental awareness

The regression results showed a significant correlation at the 1% level with local low-carbon awareness. Moreover, it had a correlation coefficient of more than 0.6, ranking second among all influencing factors. This demonstrates that low-carbon awareness promotes local research and the application of low-carbon patents, thereby promoting low-carbon patent cooperation between localities.

6. Spatial evolution of the low-carbon patent cooperation networks of the five urban agglomerations along the eastern coast

As seen above, the eastern region contains the main provinces for low-carbon patent cooperation in China. Urban agglomeration is an important carrier for the connection and agglomeration of innovative elements. The five major urban agglomerations along the eastern coast are important growth poles for the high-quality economic development of China. Therefore, this study analyzes the network structure and influencing factors of low-carbon patent cooperation based on the five major urban agglomerations in eastern China.

6.1. Statistical characteristics

The basic statistical characteristics of the network were calculated in Gephi using the five urban agglomerations, i.e., BTH, YRD, PRD, SP, and WTS, as spatial units. As shown in Table 11,

TABLE 9 Statistical characteristics of the interprovincial low-carbon patent cooperation network between the eastern, central, and western regions of China.

Region	Year	Number of nodes	Number of edges	Average degree	Average weighted degree
East-east	2001	8	10	2.5	16.5
	2011	10	31	6.2	437.6
	2021	10	45	9	2015.6
Central-central	2001	-	-	-	-
	2011	9	11	2.444	8.889
	2021	9	32	7.111	83.778
West-west	2001	-	-	-	-
	2011	11	11	2	12.727
	2021	12	52	8.667	115.333
East-west	2001	8	7	1.75	3
	2011	19	43	4.526	44.526
	2021	22	103	9.364	363.091
East-central	2001	10	10	2	6.2
	2011	19	53	5.579	102.842
	2021	19	84	8.842	474
Central-west	2001	2	1	1	2
	2011	16	20	2.5	8.5
	2021	21	78	7.429	75.143

TABLE 10 Correlation coefficients between the weighted degree of the low-carbon patent cooperation network and influencing factors.

Influencing factor	Detector	Correlation	*P*
Quality of economic development	GDP per capita	0.5146	0.0733
	Per capita disposable income of residents	0.5463	0.0627
	Value added of the secondary and tertiary industries as a percentage of GDP	0.4657	0.0283
Financial support	Local government fiscal expenditure as a percentage of GDP	0.4333	0.0506
	Science and technology expenditure as a percentage of local government fiscal expenditure	0.5703	0.0570
Local scientific research level	R&D expenditure of industrial enterprises above the designated size	0.6022	0.0027
	Number of effective R&D invention patents of industrial enterprises above designated size	0.7155	0.0133
	Number of undergraduates and college students	0.4267	0.0404
Local awareness	Low-carbon search index	0.6801	0.0000

the network density of the five urban agglomerations increased significantly over time, with the patent cooperation between cities, especially within urban agglomerations, getting closer. In 2021, all cities in the urban agglomerations participated in the low-carbon patent cooperation network, except for the WTS. The low-carbon patent cooperation between BTH and the YRD was in the lead in terms of both network connectivity and connection strength.

6.2. Spatial pattern

As shown in Table 12, in 2001, no obvious core-periphery structure was observed in the urban agglomerations, except for BTH, where the low-carbon patent cooperation network showed a single-core structure with Beijing as the core. In 2021, the low-carbon patent cooperation networks in BTH, YRD, PRD, and WTS showed a single-core structure with Beijing, Shanghai, Guangzhou, and Xiamen as the core, respectively, and that of SP showed a dual-core structure with Jinan and Qingdao as the cores. Specifically, the low-carbon patent cooperation network within the PRD was based on the cooperation of Guangzhou and Shenzhen with Dongguan, Foshan, and Huizhou; cooperation within the YRD was based on the cooperation of Nanjing and Shanghai with Suzhou and Hangzhou; cooperation within BTH was based on the cooperation of Beijing with Shijiazhuang and Tianjin; that within the SP was based on the cooperation of Jinan and Qingdao with Yantai and Binzhou; and that within the WTS was based on the cooperation of Xiamen and Fuzhou with Zhangzhou and Quanzhou.

TABLE 11 Statistical characteristics of the low-carbon patent cooperation networks of the five urban agglomerations along the eastern coast of China.

Year	Urban agglomeration	Number of nodes	Number of edges	Network density	Average clustering coefficient	Average path length	Average degree	Average weighted degree
2001	BTH	3	2	0.667	0.000	1.333	1.333	5.333
	PRD	2	1	1.000	0.000	1.000	1.000	1.000
	YRD	2	1	1.000	0.000	1.000	1.000	2.000
	SP	2	1	1.000	0.000	1.000	1.000	1.000
	WTS	2	1	1.000	0.000	1.000	1.000	1.000
2021	BTH	10	25	0.556	0.825	1.444	5.000	181.200
	PRD	9	21	0.583	0.826	1.417	4.667	122.444
	YRD	16	68	0.567	0.824	1.443	8.500	228.500
	SP	12	30	0.455	0.759	1.545	5.000	26.333
	WTS	8	10	0.357	0.761	1.375	2.500	24.000

TABLE 12 Spatial pattern of interurban low-carbon patent cooperation networks in 2001, 2011, and 2021.

Year	Urban agglomeration	Nodes (top 10 by weighted degree)	Edges (top 10 by weight)
2001	BTH	Beijing (8), Tianjin (6), and Langfang (2)	Beijing-Langfang (2), and Beijing-Tianjin (6)
	PRD	Guangzhou (1) and Huizhou (1)	Guangzhou-Huizhou (1)
	YRD	Shanghai (2) and Nanjing (2)	Shanghai-Nanjing (2)
	SP	Qingdao (1) and Yantai (1)	Qingdao-Yantai (1)
	WTS	Xiamen (1) and Quanzhou (1)	Xiamen-Quanzhou (1)
2021	BTH	Beijing (823), Tianjin (370), Shijiazhuang (272), Baoding (137), Tangshan (53), Zhangjiakou (48), Chengde (35), Langfang (30), Cangzhou (28), and Qinhuangdao (16)	Beijing-Tianjin (325), Beijing-Shijiazhuang (224), Baoding-Beijing (108), Beijing-Tangshan (42), Beijing-Zhangjiakou (31), Beijing-Chengde (30), Beijing-Langfang (28), Beijing-Cangzhou (23), Baoding-Shijiazhuang (20), and Shijiazhuang-Tianjin (17)
	PRD	Guangzhou (396), Shenzhen (216), Dongguan (138), Foshan (108), Huizhou (82), Zhuhai (60), Zhaoqing (40), Jiangmen (38), and Zhongshan (24)	Dongguan-Guangzhou (91), Guangzhou-Shenzhen (89), Foshan-Guangzhou (58), Guangzhou-Zhuhai (57), Huizhou-Shenzhen (57), Dongguan-Shenzhen (34), Guangzhou-Jiangmen (31), Foshan-Shenzhen (28), Guangzhou-Zhaoqing (27), and Guangzhou-Huizhou (25)
	YRD	Shanghai (874), Nanjing (557), Hangzhou (520), Wuxi (506), Ningbo (415), Suzhou (286), Changzhou (100), Jiaxing (97), Nantong (67), and Zhenjiang (51)	Shanghai-Wuxi (408), Hangzhou-Ningbo (231), Shanghai-Suzhou (117), Nanjing-Shanghai (108), Nanjing-Suzhou (96), Hangzhou-Shanghai (90), Nanjing-Ningbo (90), Hangzhou-Nanjing (71), Ningbo- Shanghai (68), and Changzhou-Nanjing (56)
	SP	Jinan (81), Qingdao (81), Weifang (26), Weihai (24), Yantai (24), Dongying (22), Binzhou (18), Zibo (16), Dezhou (7), and Rizhao (7)	Jinan-Qingdao (29), Qingdao-Yantai (13), Binzhou-Jinan (12), Qingdao-Weifang (11), Qingdao-Weihai (10), Dongying-Qingdao (9), Dongying-Zibo (7), Jinan-Weihai (7), Jinan-Tai'an (6), and Dezhou-Jinan (5)
	WTS	Xiamen (66), Fuzhou (49), Zhangzhou (43), Quanzhou (17), Ningde (10), Putian (5), Shantou (1), and Chaozhou (1)	Xiamen-Zhangzhou (38), Fuzhou-Xiamen (21), Fuzhou-Quanzhou (10), Ningde-Fuzhou (9), Quanzhou-Xiamen (6), Zhangzhou-Fuzhou (5), Fuzhou-Putian (4), Quanzhou-Putian (1), Xiamen- Ningde (1), and Shantou-Chaozhou (1)

6.3. Betweenness centrality

The betweenness centralities of the five urban agglomerations are reported in Table 13. In 2021, Beijing, Guangzhou, Nanjing, Jinan and Fuzhou ranked first in terms of betweenness centrality, indicating their absolute leadership for the path of the low-carbon patent cooperation network and their core position in the network.

6.4. Closeness centrality

In 2021, cities that ranked high in terms of closeness centrality in the low-carbon patent cooperation networks of the five urban agglomerations are Beijing, Tianjin, and Shijiazhuang in BTH; Guangzhou, Shenzhen, Foshan, and Dongguan in PRD; Nanjing, Shanghai, Hangzhou, and Suzhou in YRD; Jinan, Qingdao, and

TABLE 13 Betweenness centrality of the nodes in the low-carbon patent cooperation network in 2021 (betweenness > 0).

BTH	Betweenness	PRD	Betweenness	YRD	Betweenness	SP	Betweenness	WTS	Betweenness
Beijing	9.83	Guangzhou	7.75	Nanjing	17.50	Jinan	20.08	Fuzhou	4.00
Tianjin	5.33	Shenzhen	3.75	Shanghai	11.00	Qingdao	8.92	Xiamen	1.50
Shijiazhuang	3.75	Foshan	2.25	Hangzhou	8.23	Weifang	3.33	Quanzhou	0.50
Baoding	0.83	Dongguan	1.25	Suzhou	5.40	Yantai	1.92		
Zhangjiakou	0.25			Ningbo	3.40	Zibo	0.67		
				Changzhou	2.77	Dongying	0.58		
				Wuxi	1.60	Weihai	0.25		
				Zhenjiang	1.60	Dezhou	0.25		
				Huzhou	0.33				
				Nantong	0.17				

Weifang in SP; and Fuzhou, Shantou, and Chaozhou in WTS (Table 14). These cities occupied a prominent position in the network. This suggests that these nodes are closer to other innovative entities in the low-carbon patent cooperation networks of urban agglomerations in China. The shorter path length also enables these nodes to acquire network resources or search for partners in a shorter time and with greater efficiency than other nodes.

7. Influencing factors of the low-carbon patent cooperation network structure in urban agglomerations

7.1. Selection of influencing factors

The correlation between the weighted degree of the low-carbon patent cooperation networks of the urban agglomerations and the influencing factors was calculated with the weighted degree of the urban agglomeration networks in 2021 as the dependent variable and the number of patent applications, per capita GDP, low-carbon search index, the total volume of post and telecommunications business, and actually utilized value of foreign direct investment as independent variables. Since the 2021 Statistical Yearbook has not been published yet, data from 2020 were used for all independent variables, except for the low-carbon search index, for which data from 2021 were used.

7.2. Results of influencing factors

The gray relational analysis results in Table 15 show that the correlation and ranking of the influencing factors vary among urban agglomerations. The number of patent applications ranked second in terms of correlation in the YRD, SP, and BTH. This indicates that innovation capability has a strong correlation with the weighted degree of the interurban low-carbon patent cooperation networks in urban agglomerations. The total volume of post- and telecommunications business and per capita GDP generally ranked fourth or fifth, except that the former factor ranked first in the PRD and the latter ranked third in the WTS. The higher the levels of economic development and informatization, the greater the possibility of low-carbon patent cooperation. The low-carbon search index represents local awareness of low-carbon development. This influencing factor ranked highest in terms of correlation in the YRD, SP, and BTH and ranked second in the PRD and WTS. This demonstrates the importance of low-carbon development awareness to low-carbon patent cooperation in urban agglomerations. The utilized value of foreign direct investment represents a city's level of technology imported from overseas through foreign direct investment. Foreign investment can quickly drive local industrial development and promote urban industrial transformation and development, thereby promoting local low-carbon patent cooperation.

TABLE 14 Closeness centrality of the top 10 nodes in the low-carbon patent cooperation network in 2021.

BTH	Closeness	PRD	Closeness	YRD	Closeness	SP	Closeness	WTS	Closeness
Beijing	1.00	Guangzhou	1.00	Nanjing	1.00	Jinan	1.00	Fuzhou	1.00
Tianjin	0.90	Shenzhen	0.89	Shanghai	0.94	Qingdao	0.85	Shantou	1.00
Shijiazhuang	0.82	Foshan	0.80	Hangzhou	0.83	Weifang	0.73	Chaozhou	1.00
Baoding	0.75	Dongguan	0.80	Suzhou	0.83	Yantai	0.69	Xiamen	0.83
Zhangjiakou	0.69	Zhaoqing	0.67	Changzhou	0.79	Dongying	0.65	Quanzhou	0.71
Chengde	0.64	Jiangmen	0.67	Wuxi	0.75	Weihai	0.65	Zhangzhou	0.63
Qinhuangdao	0.64	Zhuhai	0.62	Zhenjiang	0.75	Zibo	0.61	Ningde	0.63
Tangshan	0.60	Huizhou	0.57	Ningbo	0.71	Binzhou	0.61	Putian	0.63
Cangzhou	0.56	Zhongshan	0.57	Huzhou	0.68	Dezhou	0.58		
Langfang	0.56			Nantong	0.65	Rizhao	0.55		

8. Conclusions and implications

8.1. Conclusions

The present study analyzes the number of low-carbon patent applications and the structural characteristics of the cooperation networks in China at the provincial and urban agglomeration levels using social network analysis based on data from the Incopat global patent database since 2001; it reveals the climate governance pattern established in China to achieve the goals of peak carbon emissions and carbon neutrality. The following conclusions were reached.

The total number of low-carbon patent applications in China increased annually. Specifically, two characteristics are present in the number of low-carbon patent applications in China due to local economic development, scientific research, and policies. First, there were great changes in the number of low-carbon patent applications. Second, the number of low-carbon patent applications varied significantly between provinces, but such regional differences have been decreasing.

In terms of provincial cooperation, China has formed an effective low-carbon cooperation network as a whole, showing obvious spatial correlation and spillover effects and increasing clustering. In terms of individual network characteristics, Beijing, Jiangsu, Guangdong, Shanghai and other provinces along the eastern coast occupy a core position in the network and play an important role in utilizing structural holes and bridging. In terms of segmentation, three types of blocks have been formed: bidirectional spillover, main benefit, and broker blocks. There is a clubbing effect between the blocks. In terms of regional connections, the interregional low-carbon patent cooperation network is not only more closely connected but also has stronger connection strength than the intraregional interprovincial cooperation network, except for east-east cooperation.

In terms of urban agglomeration, the size of the low-carbon patent cooperation networks of all five urban agglomerations increased significantly over time, with the interurban patent cooperation getting closer. The cooperation within the urban agglomerations showed an integrated radial pattern centered on the central city of the urban agglomeration. GRA reveals that urban innovation capability, economic development, low-carbon development awareness, level of technology import from overseas, and informatization level are highly correlated with the weighted degree of the low-carbon cooperation network.

8.2. Implications for public health

At present, China is in a critical period of low-carbon transformation. In addition, it may be difficult to control the global impact of the COVID-19 pandemic in a short period of time. Therefore, local governments need to combine local economic development with low-carbon development and integrate low-carbon development into all aspects of local development (43). Accordingly, the following suggestions are proposed. First, the COVID-19 pandemic has restricted and affected exchanges and cooperation between regions to varying degrees. Therefore, efforts should be made to explore the potential for cooperation between patent applicants in the low-carbon field. By developing technical information-sharing platforms, promoting urban digitalization, and establishing incentive mechanisms, the low information transmission efficiency caused by geographic and technological distance can be overcome, and new cooperation can be established between patent applicants on an ongoing basis, thereby expanding the breadth of cooperation and exploring the potential for cooperation within the low-carbon patent cooperation network.

Second, important provinces or cities in the low-carbon patent cooperation network should be encouraged to play a leading role. While making every effort to prevent COVID-19, core provinces or cities should be encouraged to carry out further cooperation (44). Moreover, efforts should be made to facilitate low-carbon patent cooperation between the core and peripheral provinces or cities under the leadership of the core provinces or cities. In this way, the internal resource allocation of the network can be optimized, the sustainable development of the low-carbon industry promoted, the bridging role of universities and research institutes further enhanced, and the resources of enterprises fully utilized.

TABLE 15 Correlation between the weighted degree of nodes in the low-carbon patent cooperation networks of the five urban agglomerations along the eastern coast of China and the influencing factors.

Influencing factor	PRD		YRD		SP		BTH		WTS	
	Correlation	Rank	Correlation	Rank	Correlation	Rank	Correlation	Rank	Correlation	Rank
Number of patent applications	0.736	3	0.787	2	0.808	2	0.865	2	0.858	4
GDP per capita	0.729	4	0.640	5	0.654	5	0.731	4	0.869	3
Low-carbon search index	0.782	2	0.800	1	0.834	1	0.899	1	0.888	2
Total volume of post and telecommunications business	0.785	1	0.769	4	0.698	4	0.682	5	0.815	5
Actually utilized value of foreign direct investment	0.719	5	0.784	3	0.718	3	0.855	3	0.896	1

Third, actions should be taken to establish cross-regional cooperative groups for low-carbon patent development. The burden of the COVID-19 pandemic on the economically underdeveloped central and western regions is self-evident. Therefore, efforts should be made to fully exploit the technical advantages and economic assistance of industry-university-research organizations in the eastern provinces, cities, and urban agglomerations, promote the interconnections and interactions between the eastern and central regions, and strengthen the leading role of the east for the west. This will contribute to achieving cross-regional low-carbon technology cooperation and establishing a reasonable spatial pattern for promoting the development of low-carbon technologies for energy conservation and environmental protection in China.

Finally, more financial support should be provided to increase R&D investment and efforts, especially for the R&D of low-carbon technologies. Local governments should seize the development opportunities brought by the COVID-19 pandemic and devote great efforts to developing low-carbon technologies to achieve corner overtaking in regional development.

8.3. Theoretical contributions

First, this study attempts to investigate China's low-carbon patent cooperation network at the national, urban agglomeration, and regional levels, employs the existing network analysis method in a vertical three-dimensional manner, and reveals the pattern characteristics of the low-carbon patent cooperation network in different dimensions. It breaks the limitation of the single-dimensional perspective of traditional network research and expands the theoretical system of the geography of innovation.

Second, this study analyzes the position and role of each node city in the innovation networks at the urban agglomeration, regional, and provincial levels, which not only helps identify the innovation functions and roles of cities but also facilitates the deepening of the theoretical research of innovative cooperation between cities.

8.4. Limitations and directions for further research

Despite its contribution, this study has some limitations. First, this study is limited to China and did not investigate the low-carbon patent cooperation between countries in the context of globalization. Second, the influencing factors selected in the study are not comprehensive enough due to limited data availability. In future research, the mechanisms that affect the low-carbon patent cooperation network can be further explored through other methods, such as field surveys, and further empirical studies of the influencing factors using econometric methods. Third, due to space limitations, the spatial pattern and influencing factors of the national low-carbon patent cooperation network have not been analyzed at the level of prefecture-level cities. Further research could also be conducted on these aspects.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evaluation of ecological green high-quality development based on network hierarchy model for the demonstration area in Yangtze River Delta in China

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Introduction: The construction of the Yangtze River Delta ecological green development demonstration area aims to take the lead in exploring an eco-friendly development model, demonstrating and leading the higher quality integrated development of the Yangtze River Delta in China.

Methods: Through literature research, expert inquiries, and policy documents as the guidance, this study builds an ecological green high-quality development evaluation system for the demonstration area, including building an index system composed of 4 first-class indicators, 16 second-class indicators and 42 third-class indicators derived from economy, society and environment system, determining the index weight through the network analytic hierarchy process, and establishing the comprehensive evaluation index (CEI) and differential diagnosis index (DDI) of high-quality development, which is based on the relevant theory of statistical comprehensive index.

Results: The establishment of this system provides a complete theoretical support and scientific guidance for the comprehensive evaluation of high-quality ecological green development and more balanced development of the demonstration area; and it can point out the development direction for the subsequent development of the Yangtze River Delta.

Discussion: However, due to the availability of data, there is still room for further improvement in this paper. In the future research, the model can be used to evaluate the high-quality development level of the demonstration area through the relevant data of the demonstration area.

KEYWORDS

low carbon development, evaluation method, network hierarchy model, ecological green, evaluation index system

1. Introduction

The Yangtze River Delta region is a pioneer in China's economic development, social openness, innovation capacity and other aspects. It strives to build a unified market through regional integration, so as to form a joint force for development and promote high-quality development faster. The Yangtze River Delta Ecological Green Integrated Development Demonstration Zone (hereinafter referred to as the "Integrated Demonstration Zone") includes three administrative districts and counties (hereinafter referred to as "two districts and one county") under Shanghai, Jiangsu and Zhejiang. The construction of the integrated demonstration area aims to take the lead in exploring a development model, fully transform the advantages in the ecological field into the driving force of economic and social development, and finally feed back the ecological construction, so as to demonstrate and lead the comprehensive and high-quality development of the Yangtze River Delta. We took the innovation of regional integration system as a starting point to achieve common consultation, joint construction and sharing, as well as demonstrate and lead the higher quality integrated development of the Yangtze River Delta region. In the released Overall Plan for the Ecological and Green Integrated Development Demonstration Area in the Yangtze River Delta (hereinafter referred to as the "Overall Plan for the Demonstration Area"), the specific requirements for the construction of the integrated demonstration area in various fields have been deployed in detail, and the establishment of a high-quality statistical system of development level has been proposed. Therefore, according to the requirements of the plan, this paper constructs and applies a comprehensive evaluation system based on the high-quality development of the integrated development demonstration area, and quantitatively analyzes the results of high-quality development from the perspective of statistics. Therefore, this study intends to build a matching evaluation model for the high-quality development of the Yangtze River Delta region, and points out the direction for subsequent development based on this.

2. Connotation and connection of high-quality development, green development and regional integration

Ecological green integration demonstration area is the only demonstration area in China that covers both ecological green development goals and high-quality development goals (1). It is highly creative and innovative to take this demonstration area as the research object. Due to the short establishment time of the demonstration zone and the lag of relevant information release, the academic research on the integrated demonstration zone is still in its infancy. The existing research is mainly based on the official documents issued by the government, from the analysis of the development status of the integrated demonstration zone, the carding of the evaluation system and other aspects. In the existing research, some scholars closely followed the theme of "green development" of the demonstration area, evaluated the green development level of the demonstration area from three dimensions, including economic development, natural endowment and environmental governance, and diagnosed the advantages and disadvantages of green development of the demonstration area (2). Some scholars also understood the high-quality development of the demonstration area as a more adequate, balanced, comprehensive and sustainable development, and established an evaluation system to assess the construction level of the demonstration area around the overall strategic positioning and target requirements of the demonstration area (3). On the basis of building a high-quality development evaluation system, Jiaxing Municipal Bureau of Statistics carried out an empirical evaluation on the Jiaxian County (i.e., one of the "two districts and one county" in the demonstration area) under its jurisdiction, and put forward targeted countermeasures and suggestions (4). These research provide logical and methodological guidance for the in-depth study of the integrated demonstration zone, but there are still problems such as the evaluation system can not completely cover the development system, and the evaluation indicators can not be directly reflected in the evaluation results. Therefore, in order to build and apply the comprehensive evaluation system for high-quality development of the integrated demonstration area and promote the integrated demonstration area to build a high-quality development benchmark, we should first clarify the respective connotation and internal relationship of high-quality development, green development and regional integration, and then conduct comprehensive consideration to establish a comprehensive and scientific evaluation index system.

According to the relevant reports of the Chinese government and the statements made by national leaders, high-quality development is characterized by low input of production factors, high efficiency of resource allocation, low cost of resources and environment, and good economic and social benefits. Its purpose is to meet the growing needs of the Chinese people for a better life. In addition to the policy connotation, scholars also interpreted the definition of high-quality development in their respective research fields. In the previous studies, scholars mainly analyze the connotation of high-quality development from two perspectives. One is to analyze the comprehensiveness of high-quality development from the perspective of five major development concepts (innovation, coordination, green, openness and sharing). The other is to analyze the weaknesses in specific areas in the development process from the perspective of China's basic social contradictions at this stage, and high-quality development aims to complement these weaknesses (5). In addition, some scholars believe that the essence of the problem of high-quality development is to do with the problem of system construction, and goes on to emphasize that high-quality development is a comprehensive exposition supported by high-quality governance structure and oriented by high-quality society and high-quality economic coordination (6). In short, high-quality development is an efficient resource allocation and development mechanism committed to using fewer production factors to input and output higher economic and social benefits, while meeting the requirements of low resource and environmental costs. From this point of view, the connotation of high-quality development of the ecological integration demonstration area can be understood as an open construction mode that takes the green development of the ecological environment as the premise, the coordinated allocation of social elements as the basic, the active introduction of innovative resources as the driving force, and the joint construction and sharing of administrative regions as the starting point.

According to early data, the total national carbon footprint in 2017 was 299 × 107 tons, and the carbon emissions caused by production and consumption in the Yangtze River Economic Belt accounted for 85 to 95 percent of the total carbon emissions from consumption (7). The essence of green development is to diversify development goals, that is, to ensure the sustainability of natural resources while pursuing economic growth. It emphasizes the integrated and coordinated development of economic system, social system and natural system, 2014. Green development covers many fields such as current resource and energy conservation and efficient utilization, environmental pollution control, ecological restoration, circular economy, clean production, land and space planning, and is the basic way to break the constraints of resources and environment (8).

In early studies, there were practices similar to regional integration construction. For example, the Commonwealth of British West Indies Colonies was established in 1956, and its integrated administrative management system was considered to be able to effectively promote economic development (9). In the long run, regional integration is not only the general trend of global development, but also the endogenous needs of social and economic development (10). From the perspective of participants, regional integration includes government, enterprises, social organizations and other subjects. These subjects jointly participate in the integration process, in which the government plays a leading role. Through policy tools, barriers to communication and exchange within the region are eliminated, and a unified regional market is created to improve the overall welfare level of the region. It includes four stages: Trade integration, factor integration, policy integration and complete integration (11). From the perspective of cooperation content, regional integration is embodied as "functional integration" and "institutional integration". Functional integration refers to the inter regional entities breaking communication barriers, complementing and relying on each other through trade exchanges, transportation and infrastructure; Institutional integration refers to the integration of rules, agreements, treaties, mechanisms, and policies to regulate and guide each other's behavior, so as to narrow the institutional gap (12). In short, regional integration is a complex system containing many factors, which needs to be considered from the perspective of economic and social development (10). Integration is closely related to regional social and economic development. For example, some scholars have proved through empirical research that regional integration can improve the overall quality of economic development of the Yangtze River Delta urban agglomeration (13).

In general, both high-quality development and green development are systematic expositions of social and economic development from macro, medium and micro perspectives. With the tightening of resource and environmental constraints in the Yangtze River Delta, taking green ecological integration as the guide, promoting higher quality economic integration has become an important way to solve social problems (14). The high-quality development of the integrated demonstration area should seize the advantages of ecological green and integration to achieve green economy, high-quality life and sustainable development.

3. Construction of evaluation system and selection of indices

Comprehensive evaluation is to establish an indicator system for specific research objects, make an overall judgment on the content to be evaluated, and achieve quantitative results. High quality development is a systematic and dynamic comprehensive concept, covering all kinds of subjects and elements in many fields such as ecology, economy and society, and there are complex internal relationships. This paper will combine the construction steps of comprehensive evaluation and carry out research according to the following steps: build a comprehensive high-quality development evaluation system and select representative indicators. Determine the weight of each indicator; Build a high-quality development model for the integrated demonstration area.

According to the overall plan of the demonstration area, the strategic objectives of the integrated demonstration zone are the transformation of ecological advantages, green innovative development, integrated system innovation, and harmony and livability between man and nature. In combination with the policy documents, the sorting out of concepts such as high-quality development in the previous text, and the development laws of mature urban agglomeration integration, this study aims at scientific guidance and reasonable evaluation of the construction of the demonstration area, positioning the objectives of high-quality development of the integrated demonstration area as: high-value ecological transformation, sustainable economic development, high-efficiency policy coordination and high-quality living environment. The target orientation also constitutes the main dimension of this study to evaluate the high-quality development of the integrated demonstration area.

High-value ecological transformation is the environmental guarantee for the high-quality development of the integrated demonstration area. The integrated demonstration area covers a total area of 2,413 square kilometers, including many water network lakes focusing on the "one river, three lakes" of the Taipu River, Dianshan Lake, Yuandang lake and FENHU lake. The water surface rate is 18.6%, and there are 396 lakes of all sizes. The river–lake relationship in the basin and the people around it constitute a community of Destiny (15). For the water ecosystem, cross-border collaborative governance has become a relatively mature governance paradigm (16). Therefore, it is necessary to give full account of the ecological and environmental advantages of the integrated demonstration area, explore and practice the development mode of ecological priority, green development and rural revitalization, and create a new benchmark for the transformation of ecological advantages. Environmental optimization can not only reduce carbon emissions, but also improve land use and public health, thereby contributing to the conservation of biodiversity and thus supporting the efficient operation of the carbon cycle. This dimension specifically includes ecological environment governance, ecological space construction and ecological culture development.

Sustainable economic development is both the capital guarantee and the key goal of high-quality development in the integrated demonstration zone. Innovation support is an important chain connecting ecological environment protection and high-quality economy (17). Green innovation is a community of circular promotion jointly formed by green development and innovation. Green innovation can not only promote regional economic growth, but also improve the overall social welfare level (18). The high-quality development of the integrated demonstration zone should rely on the existing natural, cultural, industrial and other high-quality resources in the demonstration zone, excavate and gather more innovative elements, cultivate the industrial innovation ecosystem, and form a regional green innovation development highland. The specific content of this dimension includes two aspects: the green economy business form and the innovative development level.

The coordinated policy system is the institutional guarantee for the high-quality development of the integrated demonstration zone. The realization of high-quality economic development needs the support of system (6). A systematic system can not only provide guidance for high-quality development participants, but also constrain their behavior. Integrated institutional innovation is an inevitable requirement for the high-quality development of the demonstration area. It focuses on institutional arrangements in planning management, ecological protection, land management, factor flow, fiscal and tax sharing, public services and other fields, forms policy synergy and coordination, and realizes integrated institutional innovation of common consultation, joint construction, common management, sharing and win-win. Policy coordination includes unified planning and management system, ecological environment protection system, land management mechanism, factor flow system, fiscal and tax sharing system, public service policy, credit management system among others.

High efficiency policy coordination is the institutional guarantee for the high-quality development of the integrated demonstration area. From the perspective of the overall development trend of interconnection among economy, society and system, the realization of high-quality economic development needs the support of system (6). A prominent feature of the high-quality development of the integrated demonstration area is the harmony and livability between man and nature. The two districts and one county in the integration demonstration area have always had close economic exchanges and cultural affinity, and the residents have a strong centripetal force and sense of unity. Existing studies have shown that the higher the degree of equalization of public resources and services such as regional medical care and education, the greater the social efficiency (17). Therefore, improving the infrastructure system and public service network, carrying forward the poetic Jiangnan water culture and promoting the integration of urban and rural development is one of the key ways for the high-quality development of the integrated demonstration area. The content of this dimension includes building the cultural brand of Jiangnan Water Town, beautiful and livable rural environment, connectivity infrastructure system, high-level public service guarantee and many others.

Focusing on the evaluation objective of high-quality development of the integrated demonstration area, according to the specific requirements of the Overall Plan of the Yangtze River Delta Ecological and Green Integrated Development Demonstration Area, as shown in Table 1, the first column includes four first level evaluation indicators of economy, society, environment and system, the second column includes 16 second level indicators, and the third column includes 42 third level indicators. The selection of indicators, measurement basis, measurement methods and other specific contents follow the principle of science, comprehensiveness and operability.

4. Construction of the evaluation model

4.1. Determination of index weight

The evaluation of the high-quality development of the integrated demonstration area is a systematic and complex project. There is a relationship of mutual correlation and interaction among its evaluation indicators. For example, the planning and management system will affect the ecological and cultural development and the livable rural environment. The green economy format is also closely related to the relevant policies and systems. Other indicators also have similar correlation and impact. The analytic network process (ANP) is a further development of analytic hierarchy process (AHP). When there are many elements to be decided, and the relationship between the elements is complex, and network analytic hierarchy process can provide more optimized solutions.

This study studies whether the index layer is independent and interacts with each other, then it constructs a typical hierarchical structure, builds a judgment matrix by using expert scoring method, and then solves the super matrix. By using the super matrix, it comprehensively analyzes all the interacting and influencing factors to obtain their mixed weights, and constructs an evaluation index system.

(1) Analysis of correlation and influence of index factors

After consulting experts in relevant fields and analyzing relevant data, this study combs the influence relationship among the entire evaluation indicators, and constructs the correlation matrix table shown in Table 2, "1" in the table indicates that there is an association between the indicators in the left column and the corresponding indicators above the table.

Based on the above matrix, the indicator network relationship built by super decisions software is shown in Figure 1.

(2) Construction of evaluation model based on ANP

By analyzing the indicator system and the relationship between indicators, this paper builds a high-quality development evaluation model of the integrated demonstration area based on the network AHP method (Figure 2).

The elements of the index system of the evaluation model are divided into two parts: the control layer and the index layer. The control layer includes the target layer and the criterion layer. The indicators of the criterion layer and the criterion layer are relatively few, and the indicators are independent of each other. The traditional analytic hierarchy process can be used to obtain the indicator weight. The network layer includes 16 secondary indicators and their respective subordinate tertiary indicators, which are all affected by the control layer and interact with each other internally. Through the Super Decisions software, according to the principle of network level analysis, this study invited relevant experts and scholars to score the indicators based on the four criteria indicators (high value ecological transformation, sustainable economic development, efficient policy

TABLE 1 High-quality development evaluation indicators of Yangtze River Delta ecological green integrated development demonstration area.

Level-I	Level-II	Level-III
High-value ecological transformation (environment) Env	Ecological environment management	Water Quality (Env_{11})
		Air quality (Env_{12})
	Construction of ecological space	Percentage of greenery coverage (Env_{21})
		Percentage of forest coverage (Env_{22})
	Ecological culture development	Construction process of ecological corridor (Env_{31})
		Development and utilization of ecotourism resources (Env_{32})
Sustainable economic development (economy) Eco	Green economy	The development of sports industry (Eco_{11})
		The development of new agricultural formats (Eco_{12})
		The development of green finance industry (Eco_{13})
	Innovation-driven development	Investment attraction of innovative enterprises (Eco_{21})
		Industry-university Research Cooperation (Eco_{22})
		Innovation space and platform construction (Eco_{23})
		Digital platform construction (Eco_{24})
Efficient policy coordination (system) Sys	Planning management system	Unity of land spatial planning (Sys_{11})
		Unity of planning management platform (Sys_{12})
	Ecological environment protection system	Unity of ecological protection laws and regulations (Sys_{21})
		Unity of ecological environmental standards (Sys_{22})
		Unity of ecological environment monitoring (Sys_{23})
		Unity of ecological environment law enforcement (Sys_{24})
	Land management system	Unity of construction land use planning (Sys_{31})
		Unity of the inventory land activation mechanism (Sys_{32})
		Unity of management of acquisition, storage and transfer of construction land (Sys_{33})
	Factor flow system	Unity of enterprise registration standards (Sys_{41})
		Unity of enterprise service supervision system (Sys_{42})
		Unity of mutual recognition and sharing of talent qualifications (Sys_{43})
		Unity of cross regional transaction of element resources (Sys_{44})
	Financial and tax management system	Unity of tax collection and management (Sys_{51})
		Unity of Cross Regional Sharing of Finance and taxation (Sys_{52})
	Public service policy system	Unity of public service standards and systems (Sys_{61})
		Unity of public service sharing (Sys_{61})
	Public credit management system	Unity of public credit evaluation system (Sys_{71})
		Unity of regional credit reward and punishment system (Sys_{72})
High-quality living environment (Society) Soc	Jiangnan Water Town cultural brand	Integrated development of humanity and nature (Soc_{11})
		Traditional culture development project (Soc_{12})
		Eco-cultural tourism development Soc_{13}
	Beautiful and livable rural environment	Construction of beautiful countryside and boutique Village (Soc_{21})
		Rural ecological environment governance (Soc_{22})
	Interconnection infrastructure system	Construction of transportation network system (Soc_{31})
		New infrastructure construction (Soc_{32})
		Intelligent construction and Application (Soc_{33})
	High-level public service guarantee system	Supply of public service resources (Soc_{41})
		Facilitation level of social security services (Soc_{42})

TABLE 2 Correlation matrix between indices.

Indicator type		High-value ecological transformation (environment) Env			Sustainable economic development (economy) Eco		Efficient policy coordination (system) Sys							High-quality living environment (Society) Soc			
		Ecological environment management	Construction of ecological space	Ecological culture development	Green economy	Innovation-driven development	Planning management system	Ecological environment protection system	Land management system	Factor flow system	Financial and tax management system	Public service policy system	Public credit management system	Jiangnan Water Town cultural brand	beautiful and livable rural environment	Interconnection infrastructure system	High- level public service guarantee system
High- value ecological transformation (environment) Env	Ecological environment management							1						1	1		
	Construction of ecological space						1								1		
	Ecological culture development				1								1	1			
Sustainable economic development (economy) Eco	Green economy			1										1	1		
	Innovation-driven development											1					
Efficient policy coordination (system) Sys	Planning management system		1													1	
	Ecological environment protection system	1															
	Land management system															1	
	Factor flow system										1						1

(Continued)

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TABLE 2 (Continued)

Indicator type		High-value ecological transformation (environment) Env			Sustainable economic development (economy) Eco		Efficient policy coordination (system) Sys							High-quality living environment (Society) Soc			
		Ecological environment management	Construction of ecological space	Ecological culture development	Green economy	Innovation-driven development	Planning management system	Ecological environment protection system	Land management system	Factor flow system	Financial and tax management system	Public service policy system	Public credit management system	Jiangnan Water Town cultural brand	beautiful and livable rural environment	Interconnection infrastructure system	High- level public service guarantee system
	Financial and tax management system									1							
	Public service policy system					1											
	Public credit management system			1													
High-quality living environment (Society) Soc	Jiangnan Water Town cultural brand	1		1	1												
	Beautiful and livable rural environment	1	1		1												
	Interconnection infrastructure system						1		1								
	High- level public service guarantee system									1							

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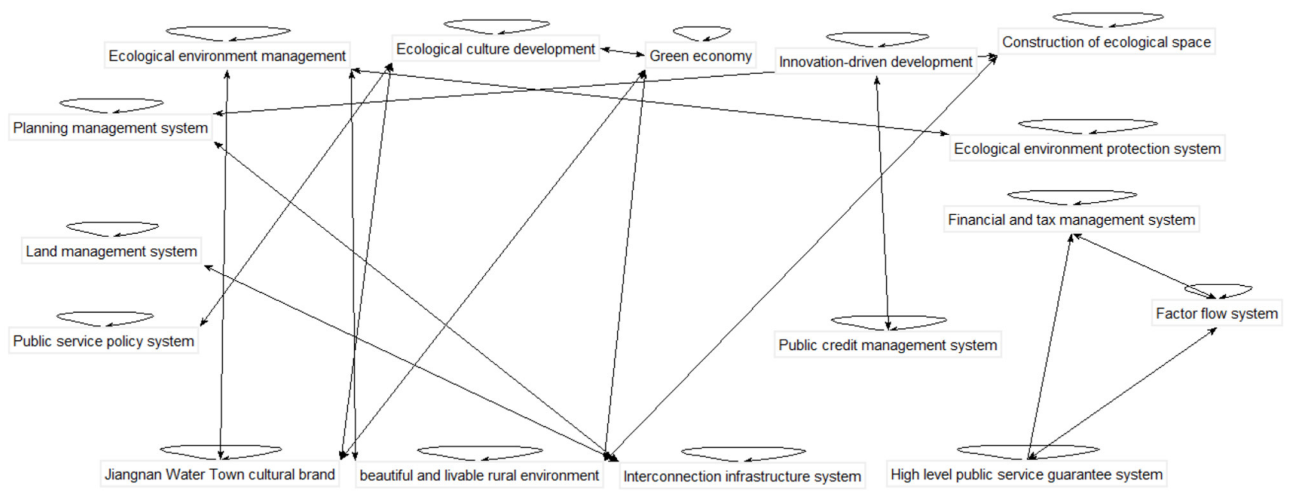

FIGURE 1
Index network diagram.

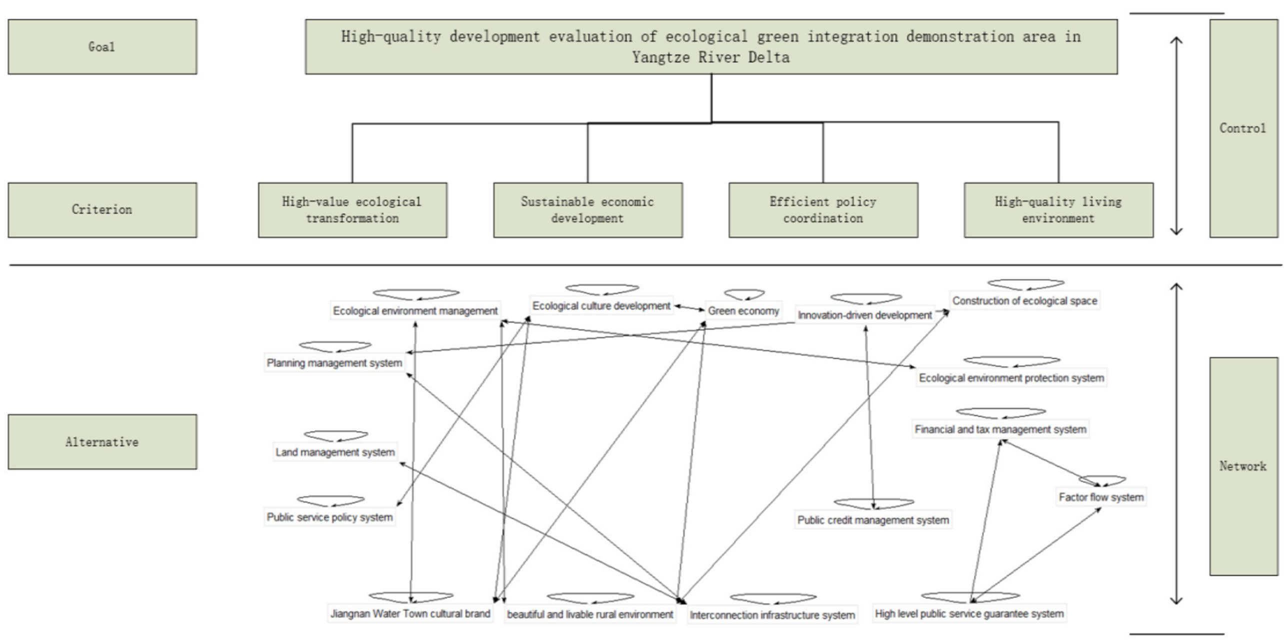

FIGURE 2
High-quality development evaluation model of Yangtze River Delta eco green integrated development demonstration area.

coordination, high-quality living environment) of the control layer. Since there are many index coefficients and the accuracy of subjective evaluation by experts is limited, this study invited experts from relevant industries to compare and score the element level indicators in pairs; The judgment matrix is constructed, and the consistency of the judgment matrix is checked. The consistency coefficient of the judgment matrix of each element and subset is <0.1, and the consistency of the judgment matrix is passed.

After the consistency test is passed, the weighted super matrix is generated by constructing the unweighted super matrix and performing normalization analysis. Finally, the weighted super matrix is stabilized, and the weight results of each evaluation index can be obtained (Table 3).

4.2. Analysis of the results

From the level of secondary indicators in Table 3, the top five secondary indicators in the weight of the high-quality development assessment system of the integrated demonstration area are ecological environment governance (0.2252), beautiful

TABLE 3 Weight of high-quality development evaluation indicators of integrated development demonstration area.

Level-II	Weight	Level-III	Global weight	Local weight
Ecological environment management	0.2252	Water Quality	0.1585	0.7040
		Air quality	0.0666	0.2960
Construction of ecological space	0.0271	Percentage of greenery coverage	0.0195	0.7189
		Percentage of forest coverage	0.0076	0.2811
Ecological culture development	0.0341	Construction process of ecological corridor	0.0231	0.6778
		Development and utilization of ecotourism resources	0.0110	0.3222
Green economy	0.0680	The development of sports industry	0.0157	0.2314
		The development of new agricultural formats	0.0315	0.4633
		The development of green finance industry	0.0208	0.3053
Innovation-driven development	0.1071	Investment attraction of innovative enterprises	0.0501	0.4673
		Industry-university Research Cooperation	0.0297	0.2772
		Innovation space and platform construction	0.0172	0.1601
		Digital platform construction	0.0102	0.0954
Planning management system	0.0064	Unity of land spatial planning	0.0030	0.4699
		Unity of planning management platform	0.0034	0.5301
Ecological environment protection system	0.0402	Unity of ecological protection laws and regulations	0.0107	0.2656
		Unity of ecological environmental standards	0.0170	0.4228
		Unity of ecological environment monitoring	0.0055	0.1373
		Unity of ecological environment law enforcement	0.0070	0.1744
Land management system	0.0017	Unity of construction land use planning	0.0004	0.2491
		Unity of the inventory land activation mechanism	0.0003	0.1573
		Unity of management of acquisition, storage and transfer of construction land	0.0010	0.5936
Factor flow system	0.0973	Unity of enterprise registration standards	0.0307	0.3156
		Unity of enterprise service supervision system	0.0092	0.0941
		Unity of mutual recognition and sharing of talent qualifications	0.0158	0.1627
		Unity of cross regional transaction of element resources	0.0416	0.4276
Financial and tax management system	0.0302	Unity of tax collection and management	0.0096	0.3181
		Unity of Cross Regional Sharing of Finance and taxation	0.0206	0.6819
Public service policy system	0.0357	Unity of public service standards and systems	0.0119	0.3333
		Unity of public service sharing	0.0238	0.6667
Public credit management system	0.0411	Unity of public credit evaluation system	0.0128	0.3125
		Unity of regional credit reward and punishment system	0.0283	0.6875
Jiangnan Water Town cultural brand	0.0544	Integrated development of humanity and nature	0.0323	0.5936
		Traditional culture development project	0.0131	0.2400
		Eco-cultural tourism development	0.0090	0.1663
Beautiful and livable rural environment	0.1606	Construction of beautiful countryside and boutique village	0.0435	0.2713
		Rural ecological environment governance	0.1170	0.7288
Interconnection infrastructure system	0.0080	Construction of transportation network system	0.0044	0.5531
		New infrastructure construction	0.0021	0.2621
		Intelligent construction and Application	0.0015	0.1848
High-level public service guarantee system	0.0629	Supply of public service resources	0.0157	0.2500
		Facilitation level of social security services	0.0472	0.7500

and livable rural environment (0.1606), innovation development level (0.1071), factor flow system (0.0973) and green economy business form (0.0680). Ecological environment governance is to give priority to ecological protection, and give play to the potential social and economic value of ecological green through the development and utilization of eco-tourism resources; Building a beautiful and livable rural environment is to promote the integration and infiltration of urban and rural development by creating a rural revitalization chain and creating a high-quality residential environment; The integrated construction of the demonstration zone promotes the agglomeration of various innovative resource elements in the region through system and mechanism innovation and environment creation, plays a role in the incubation, transformation and application of innovative achievements, and produces "aggregate effect". The unified factor flow system can save transaction costs, but also facilitate industrial agglomeration, thus creating a good business environment for integrated high-quality development; Green economy formats can closely combine the characteristics and advantages of ecological green and traditional industries, transform industrial growth poles, form new growth drivers, and provide new ideas for the sustainable development of integrated demonstration areas.

Among the above five secondary indicators, the tertiary indicators with the highest proportion of internal local weights are the excellent water quality rate (0.7040), rural ecological environment governance (0.7288), innovative enterprise introduction (0.4673), cross regional transaction unity of factor resources (0.4276), and development level of new agricultural formats (0.4633), it shows that the integrated demonstration area should grasp the mature model of basin ecological coordinated governance, and achieve high-quality development of the integrated demonstration area through modern rural construction, the introduction of innovative enterprises, and the integration of trans regional factor transactions.

4.3. Formation of evaluation indices

According to the evaluation index system, two evaluation indices are constructed to evaluate the overall situation and individual differences of high-quality development in the integrated demonstration area.

(1) Comprehensive evaluation index (CEI) for high-quality development of integrated demonstration area. The comprehensive evaluation index is a technical treatment of quantifying the evaluation results. It is a weighted synthesis of multiple indicators to form a general index. The purpose of evaluation is achieved through the comparison of indexes. The four dimensions in the high-quality development evaluation system of the integrated demonstration zone can be combined into an index separately, and then a total index can be weighted based on the weights determined in this study to form a comprehensive evaluation index. The index can be used for horizontal comparison to evaluate the comprehensive development level of each region; Vertical comparison can also be conducted to evaluate the development and changes in different years.

(2) Differential diagnosis index (DDI) of high-quality development in integrated demonstration areas. The construction of differential diagnosis index is to analyze the degree of differentiation of the development level of "two districts and one county" in the integrated demonstration area and evaluate the degree of coordination of the integrated development of the demonstration area. In this study, the differential diagnosis index is constructed by the ratio of the regional single index range (maximum minus minimum) to the index average. The index can not only study the differences among indicators at all levels, so as to analyze the specific development gap of each region and point out the direction for the subsequent development; Diversified extension research can also be conducted to analyze development differences in other directions, such as comprehensive development level and green development level.

5. Conclusion and application

This study combed the connotation of high-quality development, green development and regional integration, respectively, and found the correlation between the three. Based on the analysis of the main content and indicator composition of the high-quality development evaluation system in the integrated demonstration area, the index system and model of the evaluation system were constructed, and the index weight of the model was further determined with the help of super decision-making software. This model provides a specific method for the subsequent actual evaluation of the development process and achievements. In the follow-up study, the model can be used to calculate the ecological, economic, social and other construction achievements of the integrated demonstration area by collecting relevant data of the integrated demonstration area. This research has high application value in two aspects: (1) taking the ecological green integration demonstration area in the Yangtze River Delta as the research object, applying the network analytic hierarchy process, establishing a high-quality development evaluation index system that comprehensively covers the three spaces of ecology, life and production in the integrated demonstration area, and providing methods and ways to measure the phased achievements of high-quality development and construction; (2) the indicator system can provide reference for the high-quality development evaluation research of other urban agglomerations or economic belts with coordinated development.

Based on the analytic network process, this study built an evaluation model for the ecological green and high-quality development of the Yangtze River Delta Demonstration area, which has achieved certain research results. However, due to the availability of data, there is still room for further improvement in this paper. In the future research, the model can be used to evaluate the high-quality development level of the demonstration area through the relevant data of the demonstration area.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization and writing—review and editing: LC and XY. Methodology and writing–original draft preparation: WW. Software and investigation: LC and WW. Validation and formal analysis: XY and WW. Resources, visualization, and supervision: LC. Funding acquisition: XY. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Analysis and improvement of sports industry development and public health strategy under low-carbon economic structure

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With the continuous development of society, various industries are rising and developing rapidly. Against this background, the energy crisis has come quietly. Therefore, to improve the quality of life of residents and promote the comprehensive and sustainable development of society, it is essential to enhance the development of the sports industry and formulate public health strategies under the background of a low carbon economy (LCE). Based on this, to promote the low-carbon development of the sports industry and optimize the formulation of social public health strategies, firstly, this paper introduces the low-carbon economic structure and its role in society. Then, it discusses the development of the sports industry and the necessity of perfecting public health strategy. Finally, based on LCE's development background, the sports industry's development situation in the whole society and M enterprises is analyzed, and suggestions are put forward to improve the public health strategy. The research results show that the current development prospect of the sports industry is extensive, and the added value of the sports industry will be 1,124.81 billion yuan in 2020, up by 11.6% year-on-year, accounting for 1.14% of Gross Domestic Product (GDP). Although industrial development declined in 2021, the added value of the sports industry accounts for an increasing proportion of GDP yearly, which shows that the sports industry is playing an increasingly important role in economic growth. And through the analysis of the development of M enterprise sports industry as a whole and in different directions, this paper shows that enterprises should reasonably control the development of various industries to provide impetus for the overall development of enterprises. The innovation of this paper lies in the innovative use of the sports industry as the primary research object, and its development under LCE is studied. This paper not only supports the sustainable development of sports industry in the future, but also contributes to improving public health strategy.

KEYWORDS

low carbon economy, sports industry, public health, GDP, sustainable development

1. Introduction

Under the background of social evolution, the demand for energy in all sectors of society is also increasing, and the energy crisis caused by it is also deepening. Therefore, in order to promote the sustainable development of society and improve the utilization rate of energy, the concept of low-carbon development came into being. Under the theoretical framework of sustainable development economics, low carbon economy (LCE) should be the economy with the lowest carbon emission, ecological environment cost and socio-economic cost, and it is an economy with strong ecological sustainability that can improve the self-regulation ability of the earth's ecosystem (1). The image generalization and realistic form of low-carbon economic development is a theory of low-carbon economic development (2). Developing LCE is an urgent requirement and strategic task to promote scientific development, and the key is to carry out the ecological revolution of the energy economy (3). Developing LCE and realizing low-carbon development is a systematic project to develop LCE. Based on this, the development of many social industries tends to the concept of low-carbon development. As one of the pillar industries of society, the sports industry not only plays an essential role in social development but also provides critical support for improving public health system. Therefore, it is equally important to evaluate the development of the sports industry under the background of low-carbon economic development, which is necessary for improving public health strategies, and many researchers have studied it at present.

Under the current low-carbon economic structure, how to develop various industries has also become an essential issue in the recent social reform. Among them, the sports industry, as one of the pillar industries in society, has a far-reaching impact on the public. Therefore, developing the sports industry under the low-carbon economic structure is also necessary. There are many defects in the current sports industry, the most serious of which is that the structure of the sports industry is seriously flawed, and its development is unbalanced and unscientific. It only pays attention to a certain sporting goods industry, sports clothing industry and other specific industries and does not pay enough attention to and invest in some future core industries and new industries, including the sports animation industry and sports information industry, which has seriously affected the all-round development of the sports industry. Based on this, to promote the comprehensive development of the sports industry, how to develop the sports industry reasonably under the low-carbon economic structure and thus promote public health is a significant social problem.

Based on this, this paper first discusses the theory of sports industry development and public health under the low-carbon economic structure. Then the relationship between the development of the sports industry and public health is expounded. Finally, based on the background of green economy development, the future effect of the sports industry is studied. The innovation of this paper is to check the development of the sports industry under the new situation of LCE and analyze its future development strategy. This paper not only supports the sustainable development of the sports industry, but also contributes to improving the social public health system.

2. Literature review

The emergence of the concept of low Carbon economy has significantly impacted social development, which can be found in many research works. Semieniuk et al., Wang et al. (4) contended that climate change had become the most popular topic worldwide for profound and complex reasons. From the perspective of the earth's formation and the interaction between living matter and dead matter, the air is the first element to create and maintain life. Their research finding implied climate change was a top priority for the human environment. Accordingly, in today's increasingly severe environmental pollution, vigorously developing LCE has become a crucial task of society (4). Keshkar et al. (5) stated that the sports industry was the sum of similar economic sectors offering sports products for social demands. The sports industry was integral to the national economy and industrial system. Developing the sports industry in line with the law of the sports economy was conducive to international standards with the classification method. As a new growth point of the national economy, the sports industry has already embraced preliminary conditions.

Nevertheless, there were also many difficulties (5). Weight et al. (6) warranted the sports industry's substantial role in improving public health strategy (PHS). At the same time, to catch up with LCE, continuously optimizing the sports industry was extremely important. Hence, to maintain a sustainable sports industry and promote PHS, optimizing the sports industry by extending the LCE structure could help increase social development points (6).

As far as the above literature review is concerned, the development of LCE is relatively mature. Under the background of LCE, it is urgent to optimize the development strategy of the sports industry to better conform to the concept of low-carbon development. At present, the research on low-carbon economic structure only stays in the study on its development and the effect of its application in some narrow structural levels. Still, there is little research on its overall social development level. Therefore, to reasonably reveal the influence of low-carbon economic structure on the whole society, this paper designs to study the impact of the development of the sports industry on the healthy development of the social public under the low-carbon economic structure to explore the influence effect of the development of low-carbon economic system on the whole society.

3. Development of sports industry under LCE

3.1. LCE structure

As an economic term, LCE was formally proposed by the British government in 2003 in the context of climate change concerns and the need to maintain national energy security (7). Since then, LCE has received close attention from the international community. The development mode of LCE is a historical progress trend and a new social and economic form of the postindustrial society in the transition from traditional industrial civilization to a higher ecological civilization (8). Currently, research on trade problems caused by climate change mainly involves trade carbon leakage and trade-implied carbon, border tax adjustment & carbon tariff, carbon footprint accounting standards, and carbon label certification system, carbon trading, and clean development mechanism (9). They are explained in detail below.

3.1.1. Carbon leakage

It is defined under the United Nations Framework Convention on Climate Change. Carbon leakage occurs when high-carbon emission industries and enterprises in industrialized countries (usually with strict low-carbon environmental regulations) transfer the high-carbon emissions production to developing countries. The developing nation usually lacks mandatory emission reduction obligations. As a result, governments, and regions with loose carbon emission regulations see a substantial rise in carbon emissions, resulting in "false" carbon emission reduction in developed countries. That is to say, the problem of carbon emissions in developing countries has become more serious, even causing carbon emissions to increase globally. Usually, the carbon leakage degree is usually calculated and measured by the ratio of the carbon dioxide (CO_2) emissions ratio of countries with higher domestic emission reduction and governance actions outside their borders to their domestic CO_2 emission reductions (10).

3.1.2. Trade-implied carbon

Trade-implied carbon is a fundamental concept in studying the relationship between international trade and LCE from the perspective of trade and the environment. Although trade-implied carbon is a new concept in the research of LCE, the implied concept has a long history. For a long time, the implicit energy and implicit carbon emissions of trade products have been ignored in traditional international trade research. Until recently, with the growing concern of the international community about global warming, the implicit energy and implicit carbon emissions of international trade have been gradually taken seriously (11).

3.1.3. Trade and carbon accounting

Carbon accounting refers to accounting for Greenhouse Gas (GHG) emissions in the production process of enterprises. Carbon accounting mainly targets major carbon emission bodies like enterprises. Thus, scientific carbon accounting can help identify the weak links between energy utilization and environmental protection in enterprises or product manufacturing. Thereby, it encourages enterprises to adopt Energy-Conservation and Emission Reduction (ECER) technologies and improve management measures. Ultimately, their international competitiveness can be strengthened (12).

3.1.4. Trade and carbon footprint labeling

A carbon footprint label is the main form of low-carbon product certification. It refers to the accounted GHG emissions in the production process of products. It marks the carbon footprint on the product label exponentially to inform consumers of the carbon information of products and guide them to choose low-carbon products to achieve ECER (13).

3.1.5. Trade and border tax adjustments

The border tax adjustment and other measures have been proposed to comply with the climate change policy. For the non-cooperative cross-border pollution problem, it will be the best policy choice to levy import tariffs on illegally polluting countries (14).

3.1.6. Trade and carbon tariffs

Carbon tariff refers to the special tariff on CO_2 emissions of imported energy-intensive products with high pollution proposed by Europe, America, and other developed countries (15).

With the development of LCE, the identification of carbon emission responsibility in international trade has increasingly become the focus of debate in international climate negotiations (16). There are two main criteria for determining the responsibility of international trade for carbon emissions: the producer responsibility principle that directly causes pollution, and the consumer responsibility principle that causes pollution (17). Obviously, developed countries can falsely reduce the total carbon emissions reported in China by replacing domestic production with imports, but the generation of carbon leakage does not help to reduce global greenhouse gas emissions (18). Therefore, in the future international climate negotiations, the accounting of greenhouse gasses in a country should not be limited to the national boundaries, but should be comprehensively considered from the production and consumption of goods or services to redefine the carbon emission responsibility. At present, the research on trade carbon emissions is changing from producer responsibility to consumer responsibility, which may lead to a new global carbon reduction strategy, so it must be paid full attention (19). The low-carbon economic structure formed on this basis has also become an important reference index for the development of various industries in the future.

Low-carbon economic structure is the basic industrial structure based on the development of LCE. From the relationship point of view, different industries influence and promote each other, which has something in common and provides a basic guarantee for industrial structure adjustment. At present, the general trend of the overall industrial structure of LCE is developing from the traditional structure of agriculture and industry to the tertiary industry such as service industry and tourism. Meanwhile, in the internal development process of various industries, the working methods and operation modes are constantly optimized. For example, when the agricultural industry is developing, it has begun to develop from the traditional extensive business model to the intensive and refined direction, which makes the limited land resources play a greater role and create more benefits. Moreover, various agricultural enterprises are also developing in the direction of branding, introducing professional production equipment and integrating regional culture into agricultural products in combination with regional characteristics. This new model improves the social benefits of products on the basis of ensuring the economic benefits of agricultural industry. In addition, in view of the problems of carbon emission and land pollution, agricultural workers have also begun to study ways to save water resources, and conducted in-depth research on the rational selection of fertilizer types and fertilization methods, with the aim of combining land use with land cultivation and promoting the sustainable development of agricultural industry. This scientific management model has effectively alleviated the carbon emission problem to a certain extent and achieved the goal of low-carbon agricultural management. Therefore, how to develop the sports industry in this context is also an important issue.

3.2. Development of the sports industry

The sports industry is a new driving force for national economic growth. While providing sports products for society, it also improves the physical quality of residents, enhancing national spirit, achieving social progress, and enhancing international influence (20). As a sunrise industry, sports greatly impact social and economic development and determine citizens' well-being. It is a rising growth point of China's social and economic development. Therefore, seizing this new opportunity by following the market rules can cope with the problems and drawbacks in developing the sports industry. For example, alleviating the unbalanced development can China help realize the healthy development of the sports industry and make China an intensely competitive nation (21).

The new statistical classification divides China into sports goods and related products manufacturing, sports service, and sports field facilities construction. The sports service industry includes sports management activities, sports competitions & performances, sports fitness & leisure activities, sports venues & facilities management, and other subcategories (22). Figure 1 shows the refined classification of the sports industry.

As per Figure 1, the sports industry has formed three main levels since its development: upstream sports events, midstream sports media, and downstream sports derivative industries (23). Figure 2 shows the industrial chain structure of the sports industry.

In Figure 2, the development of sports industry has been very mature, and it has promoted the development of social industries in a great range. However, under the current background of low-carbon economic development, how to adjust the development direction of sports industry to meet the needs of the times has also become an important task of current social development, so this paper plays an important role in the development of sports industry (24). Sports industry chain refers to a number of enterprises that have upstream and downstream relations and ultimately provide sports products and services to consumers. The essence of sports industry chain is the value chain that provides customer value to sports consumers. The sports industry includes the sports noumenon industry, peripheral industry, sports intermediary industry, and sports industry consumers. Among them, sports noumenon industry is the core of the whole sports industry, including sports competition and mass fitness. The industrial chain of sports peripheral industries includes sports goods suppliers, sports equipment suppliers, sports clothing suppliers, sports tourism suppliers, sports gamblers, sports medical providers and sports builders. The industrial chain of sports intermediary industry includes sports advertisers, sports sponsors and sports insurance industry.

3.3. Principles and theories of public health

Public health is an ensemble system. It involves science, art, practical skills, and beliefs, guiding, maintaining, and improving the health of all. It helps the public prevent disease, prolong their life span, and promote a nation's health and efficiency through organized community efforts (25). Organized community efforts aim to build a healthy environment both physically and mentally. These measures can control diseases, reduce infections, and raise health awareness. Furthermore, organized medical staff provides early diagnosis, prevention, and treatment services. Thereby, social mechanisms can be established to ensure community members' right to access healthy living standards. Eventually, these beneficiary policies arouse citizens' birthright: health and longevity (26).

The concept of public health has the following characteristics. (1) Public health is a public social product and a public development project. There must be joint participation and collaboration of governments at all levels, communities, and different departments. (2) Public health considers the whole population as the object and concerns the health of all social members. Public health investigates human health problems collectively or at the group level. It has the goal of eliminating premature deaths and possible diseases. In particular periods such as during epidemic infectious diseases, public health mainly concerns the pathogenesis (27).

Based on personal health, public health looks into the health problems of all social members. By comparison, personal health concerns individual health problems and is the field of personal autonomy (28). From an individual perspective, in addition to genetic factors, personal lifestyles, diet, preferences, and personality often affect their health. Unlike public health, personal health extends from personal responsibility to social responsibility. Moreover, public health protects individuals from the influence of others' unsanitary or infectious diseases, strives to improve the living environment of social members, and maintains & enhances the health quality of all

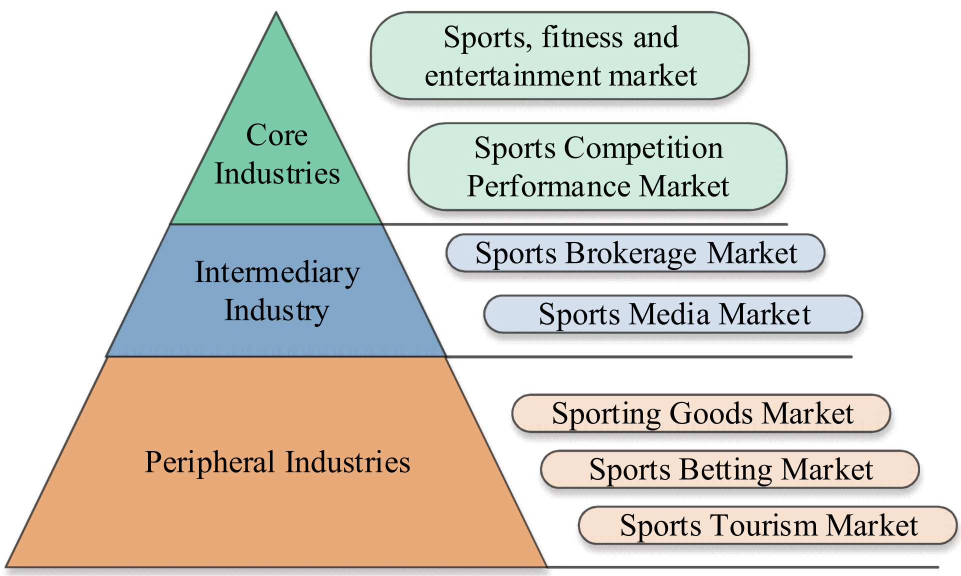

FIGURE 1
Classification of the sports industry.

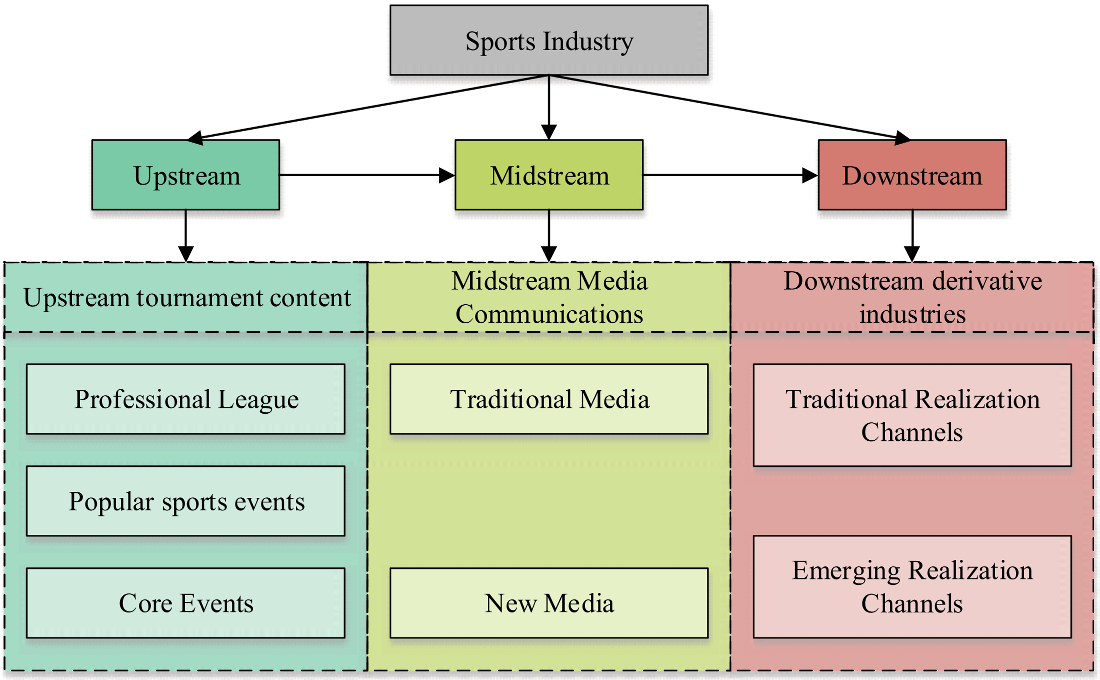

FIGURE 2
Industrial chain structure of the sports industry.

social members. Of course, public and personal health factors can also act on one another (29).

3.4. Designing the research model of sports industry development under the background of LCE

The selection of key industries should follow the benchmark of comparative advantage, correlation effect, diffusion effect, Miyohei Shinohara's two benchmark theories, technological progress, and employment (30). According to these selection benchmarks, the following corresponding index values are selected for measurement. They are the industrial added-value scale, total capital scale, employment scale, export scale, profit and tax scale, fixed asset output rate, technical level, labor productivity, capital profit and tax rate, and the proportion of scientific research personnel. At the same time, two new low-carbon indicators are introduced to meet the requirements of LCE development: carbon productivity and carbon intensity competitiveness (31). The detailed indicators are explained below (32):

a. Scale of industrial added value:

$$GY_i = Y / \sum Y \quad (1)$$

In Equation (1), GY_i is the scale of total industrial added value, and Y denotes the total industrial added value.

b. Total capital scale:

$$GZM_i = ZM / \sum ZM \quad (2)$$

In Equation (2), GZM_i is the total capital scale, and ZM represents the balance of current assets.

c. Employment scale:

$$JL_i = L / \sum L \quad (3)$$

Here, JL_i stands for the employment scale, and L mean the mean employee number.

d. Export scale:

$$EX_i = X / \sum X \quad (4)$$

Here, EX_i and X are the export scale and the total export volume.

e. Profit and tax scale:

$$SR_i = R / \sum R \quad (5)$$

In Equation (5), SR_i and R represent the scale of profits and taxes and the total amount of profits & taxes.

f. Output rate of fixed assets:

$$K_i = Y / K \quad (6)$$

Here, K_i, Y, and K stand for the output rate of fixed assets, the total added value of production, and the original price of fixed assets, respectively.

g. Technical level:

$$E_{(t)} = Y_{i(t)} / K_{i(t)}^{\partial} L_{i(t)}^{\rho} \quad (7)$$

In Equation (7), $E_{(t)}$, $Y_{i(t)}$, and t indicates the technical level, the total output value, and the year, respectively. $L_{i(t)}^{\rho}$ and $K_{i(t)}^{\partial}$ represent the mean employee number and the total amount of funds, respectively.

h. Labor productivity:

$$Q_i = \Delta Y_i / L_i \quad (8)$$

In Equation (8), Q_i, " Y_i, and L_i denote the labor productivity, the increase in output value, and the number of workers, respectively.

i. Capital profit & tax rate:

$$\delta_i = R_i / K_i \quad (9)$$

Here, δ_i, R_i, and K_i are the capital profit & tax rate, the total profit & tax, and the total amount of funds, respectively.

j. Proportion of scientific research personnel:

$$A_i = M_i / L_i \quad (10)$$

Here, A_i, M_i, and L_i represent the proportion of scientific researchers, the total number of scientific researchers, and the number of workers, respectively.

k. Carbon productivity:

$$C_i^{\text{pro}} = \left(\Delta Y / E_{\text{co}_2}\right)_i \quad (11)$$

In Equation (11), C_i^{pro}, ΔY, and E_{co_2} mean the carbon productivity, industrial added value, and the CO_2 emission, respectively. Equation (12) calculates E_{co_2}:

$$E_{\text{CO}_2} = \Sigma\left(M \times C_{\text{CO}_2}\right)_n \quad (12)$$

Here, M and C_{CO_2} are the energy consumption and the carbon emission coefficient corresponding to energy.

l. Carbon strength competitiveness:

$$C_i^{\text{int}} = \left(C_i^{pro}\right)_{\text{region}} / \left(C_i^{\text{pro}}\right)_{\text{nation}} \quad (13)$$

In Equation (12), C_i^{int}, $\left(C_i^{pro}\right)_{\text{region}}$, and $\left(C_i^{\text{pro}}\right)_{\text{nation}}$ represent the carbon strength competitiveness, the regional carbon productivity, and the national carbon productivity, respectively. These indicators can measure the extent to which an industry's carbon emission technology is ahead of the national average.

4. Experimental design and performance evaluation

4.1. Datasets collection

Part of the data sources studied in this paper are the annual sports industry announcement data published by China National Sports Bureau, including the sports industry development data from 2016 to 2021. This paper collects and analyzes these data, and obtains the results shown in Figure 3. In addition, this paper also takes M sports enterprises as the main research object. M enterprise is a leading scientific sports service provider in China. It was founded in 1996 and listed on the main board of Shanghai Stock Exchange in 2020. The company's main business is the research and development, production and sales of fitness equipment and display shelf products, including indoor fitness equipment and outdoor path products. At present, the company has formed a complete business system of fitness equipment and display shelf products. The company has achieved a leading position in the fitness equipment industry with years of manufacturing experience, product supply system, market-oriented product design, excellent product quality, and perfect supporting service capabilities. The above data sources are statistically analyzed by SPSS, and then processed and analyzed by the above formula to explore the development of sports industry.

M Enterprise is committed to providing users with professional and scientific fitness solutions, products, and services, integrating simple sports into everyone's life. It helps people build a healthy lifestyle to reach their healthcare goals, promoting a better and harmonious society.

M Enterprise was established in China's sports industry base. It has thousands of service outlets nationwide and has established an integrated online and offline service sales channel. The service sales system is almost perfect. At the same time, M enterprise prioritizes the international brand strategy. Its business involves more than 70 countries and regions, such as Europe, America, the Middle East, and Southeast Asia.

4.2. Performance evaluation

4.2.1. Analysis of the development of China's sports industry

This section statistically analyzes the overall development of China's sports industry through data collection to provide a basic reference for studying the sports industry development of M enterprises. It is expected to provide support for exploring the overall development of the industry and a reference for improving future PHS. Figure 3 shows the statistical results of the overall development of China's sports industry.

As shown in Figure 3, the added value of the sports industry was 549.44 billion RMB in 2016 and 647.48 billion Ren Min Bi (RMB) in 2017, a year-on-year (YoY) increase of 17.8%, accounting for 0.87% of the gross domestic product (GDP). In 2018, the added value of the sports industry was 781.14 billion RMB, with a YoY growth of 20.6%, accounting for 0.94% of GDP. In 2019, the added value of the sports industry was 1,007.8 billion RMB, with a YoY growth of 29.0%,

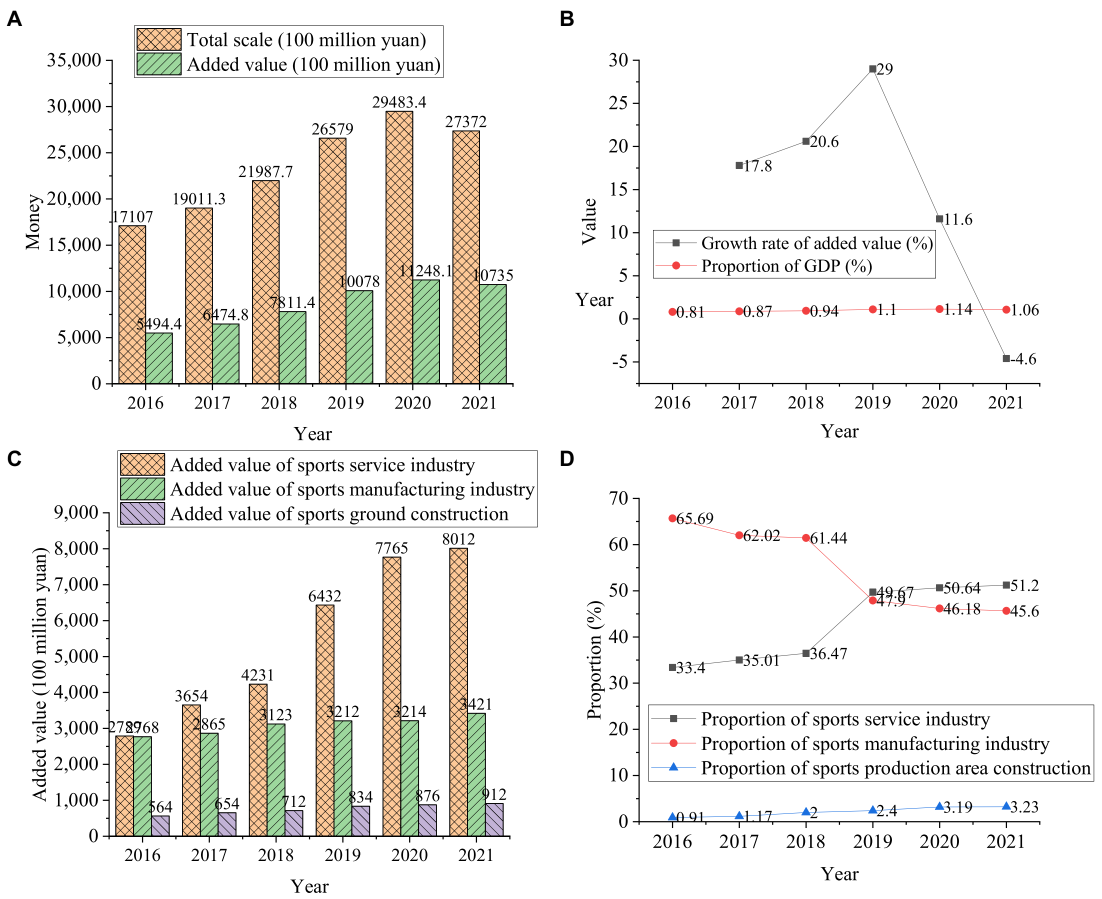

FIGURE 3
Statistics on the development of China's sports industry **(A)** refers to the overall development of the sports industry, **(B)** is the overall growth rate of the sports industry, **(C)** illustrates the development of the sports industry in different directions, and **(D)** shows the proportion of development in different directions.

accounting for 1.1% of GDP. In 2020, the added value of the sports industry was 1,124.81 billion RMB, up 11.6% YoY, accounting for 1.14% of GDP. Although industrial development declined in 2021, the proportion of the added value of the sports industry in GDP increased YoY. The result indicates that the sports industry is increasingly important in China's economic growth.

4.2.2. Analysis of the development of the sports industry in M enterprises under LCE

Low carbon economy is an important indicator of current social development. This section evaluates the development of the sports industry and M Enterprise through various indicators of LCE. It is hoped to provide a reference for the future development of enterprise and support for social PHS. Figure 4 shows the evaluation results of Enterprise M's sports industry development based on LCE.

In Figure 4, a-l in the figure refers to the above-mentioned low-carbon economic indicators. Through the analysis of the development of the sports industry as a whole and in different directions of M enterprises, this paper shows that the proportion of different industrial directions in the LCE is different, and the proportion of different industries in different low-carbon economic indicators is also different. Therefore, in order to reasonably promote the rational development of the sports industry of enterprises and meet the needs of the current social low-carbon economic development, enterprises should reasonably dominate the development of various industries to provide impetus for the overall development of enterprises. Table 1 shows the regression analysis results of the development of sports industry under the low-carbon economic structure.

In Table 1, many indicators show that the current results are significant, which shows that low-carbon economic indicators have a significant impact on the development of sports industry, so the development of low-carbon economic structure is the course of sports industry reform and development.

4.3. Discussion

In order to promote the development of sports industry under the low-carbon economic structure, this paper studies the development of sports industry based on the low-carbon economic structure, and evaluates the influence of the current low-carbon economic structure on the development of sports industry by designing low-carbon economic indicators. The results show that the current low-carbon economic structure has a significant impact on the development of sports industry, because the whole society is

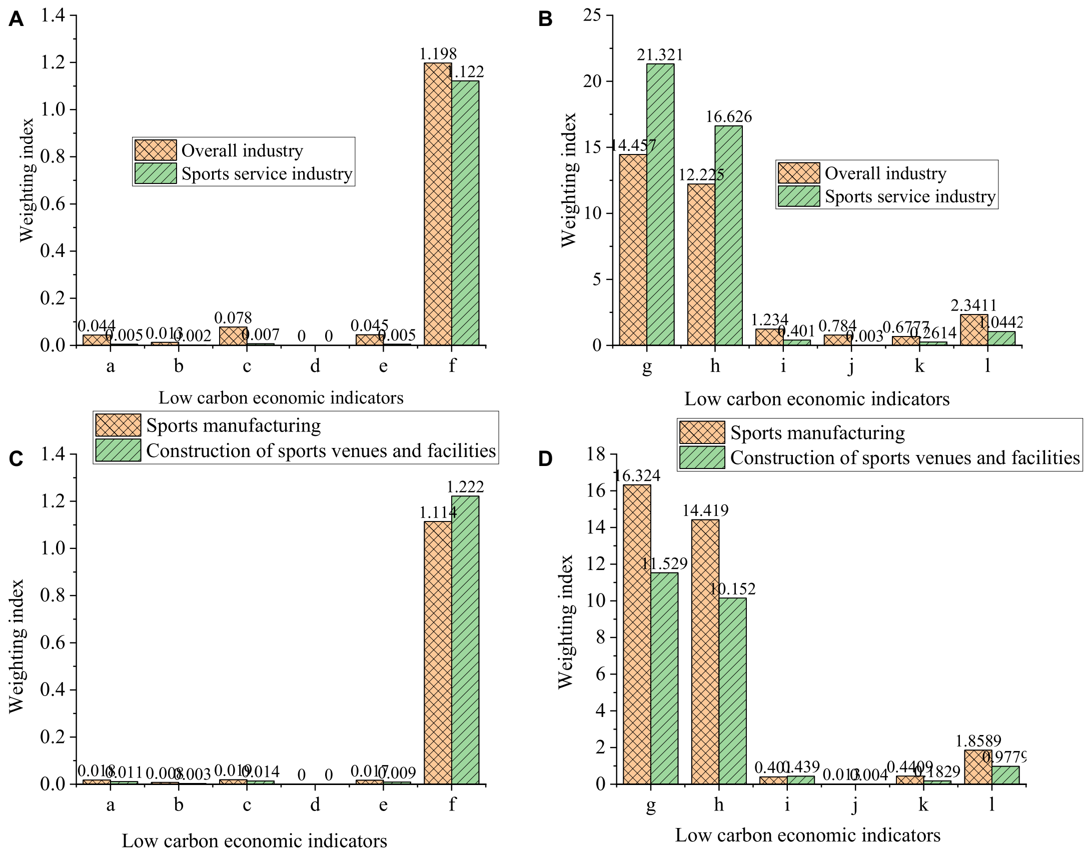

FIGURE 4
Development status of the sports industry and M enterprise **(A,B)** refer to the overall sports industry and sports service industry, and **(C,D)** is the sports manufacturing industry and the construction of sports venues and facilities.

TABLE 1 Analysis of regression results.

Low carbon economy indicators	Overall sports industry	Sports service industry	Sports manufacturing industry	Construction of sports venues and facilities
a	0.441*	0.745	0.542*	0.648*
b	0.184	0.115	0.824	0.959
c	0.541*	0.087*	0.797	0.935*
d	0.111	0.904	0.211*	0.251
e	0.632	0.249	0.718	0.128
f	0.837*	0.193*	0.915*	0.819*
g	0.651*	0.351*	0.687*	0.57*
h	0.699*	0.793*	0.874*	0.058*
i	0.908	0.901	0.854*	0.716
j	0.448*	0.761	0.032	0.677
k	0.968	0.816*	0.266*	0.957
l	0.303*	0.369	0.256	0.224

*Indicates significant results.

developing towards low-carbon economic structure, and sports industry is no exception. In addition, under the background of low-carbon economic development, improving the public health strategy is also necessary. Only by striving to improve public health can people guarantee residents' quality of life for a long time and promote the development of society. Therefore, to promote the development of social public health system, this paper puts forward the following suggestions for improving public health:(1) Formulate public policies to promote the perfection of laws and regulations. The development of LCE must be guaranteed by laws and regulations first, so China should formulate corresponding perfect laws and regulations according to China's specific national conditions to ensure the smooth development of LCE from the legislative aspect. By analyzing the specific situation of various industries in China, people should restrict enterprises with serious pollution and high energy consumption, and formulate perfect laws and regulations to escort the development of LCE. People should also constantly improve and revise the legal system according to the changing social situation to ensure the development of LCE in a better direction. (2) Formulate public policies to promote the development of low-carbon technologies. First, the state should formulate corresponding public economic policies, vigorously support the development of low-carbon technologies, and allocate certain funds for the special development of low-carbon technologies to provide a better guarantee for the development of low-carbon technologies. People can learn from developed countries' low-carbon technologies and development models, learn from their advantages, and make bold innovations to create low-carbon technologies and promotion models suitable for China 's specific national conditions, and enhance the adaptability of low-carbon technologies in China. People can also support and encourage the development of low-carbon energy and low-carbon enterprises by formulating some preferential policies, and encourage enterprises to develop low-carbon technologies. (3) Reform and improve the legal guarantee system of public health. People should conscientiously implement the laws and regulations on emergency management of public health emergencies, improve the management systems of unpaid blood donation and social medical first aid, improve the epidemic prevention and control mechanism with clear rights and responsibilities, standardized procedures and strong implementation, and clarify matters such as incident reporting, epidemic disposal, material reserves, social expropriation, social organizations and public responsibilities.

5. Conclusion

With the continuous development and progress of society, the direction of social industrial production technology is constantly optimized, so to promote society's sustainable development, the green economy model has become the main direction of social industrial production development. Based on this, in order to promote the sustainable development of sports industry under the background of green economy and improve the comprehensive level of public health strategy, firstly, this paper introduces the current development of green economy. Then the basic composition and development status of sports industry are discussed. Finally, based on the background of green economy, the current development status of sports industry and the evolution status of public health level are analyzed, and corresponding development suggestions are put forward. The results show that the current social sports industry has broad prospects for development. In 2020, the sports industry will increase by 11.6% year-on-year, accounting for 1.14% of GDP. The proportion of added value of sports industry in GDP is increasing year by year, which shows that sports industry plays a significant contribution to economic growth. As for the development of sports industry in a LCE, different branches of the industry are facing different problems. Among them, the output rate of fixed assets, technical level and labor productivity are better, while other indicators are weaker. Therefore, the development of sports industry needs to carry out targeted reforms in each branch to promote the comprehensive development of sports industry. As for the development of sports industry in a LCE, different industry branches face different problems. Among them, the output rate of fixed assets, technical level and labor productivity are better, while other indicators are weaker. Therefore, the development of sports industry needs to carry out targeted reforms in each branch to promote the comprehensive development of sports industry.

Although this paper provides suggestions for developing the sports industry and improving public health strategies, the current research only studies M enterprises, so the representativeness of the research results is not high. Based on this, the research scope will be expanded and the number of research samples will be increased in the future research, thus improving the value of this paper.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Sichuan University Ethics Committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Incentive policy optimization of scientific and technological talents and low-carbon economy analysis from the perspective of public health

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In the face of multiple challenges in stabilizing economic growth, improving people's living quality, and limiting the total amount of CO_2 emissions, firstly, this study analyzes the incentive and optimization policies of scientific and technological (S&T) talents from four aspects: incentive, cultivation, flow, and evaluation. Moreover, practical suggestions are put forward. Secondly, an optimization model of China's low-carbon economy (LCE) is implemented. The Matlab software can be adopted to solve the economic output of each department in the expected year and obtain the overall economic indicators for 2017 and 2022. Finally, the output influence and CO_2 emission influence of each industry are analyzed. The research results are as follows. (1) From the viewpoint of public health (PH), the countermeasures and suggestions of the S&T talents policy mainly include four parts: building a complete S&T talents policy system, expanding the coverage group of the policy, strictly implementing the policy of evaluating S&T talents, and improving the guarantee mechanism of relevant talents introduction policy. (2) In 2017, the primary industry, agriculture, forestry, animal husbandry, and fishery, accounted for 5.33%; the secondary industry, the energy sector accounted for 72.04%, and the tertiary industry (service industry) accounted for 22.63%. In 2022, the primary, secondary, and tertiary industry accounted for 6.09%, 68.44%, and 25.47%. (3) From the perspective of the industrial influence coefficient, the coefficient of all sectors is stable during 2017–2022. From the standpoint of CO_2 emission, China's total CO_2 emission shows rapidly increasing trend during the same period. This study has vital practical significance and theoretical value for realizing the sustainable development (SH) and transformation of the LCE.

KEYWORDS

public health, talent incentive, low-carbon economy, CO_2 emission influence, industrial influence

1. Introduction

No matter what kind of ideology, development is the eternal theme of human society, it is of great significance to study how to optimize the policy of scientific and technological (S&T) talents, guide relevant skills, explore the development direction and model of S&T skills policy from the angle of public health (PH), and create an excellent social development environment for the talents and guarantee the implementation of the strategy of rural revitalization.

In China's development, energy, as a non-renewable resource, is a key factor in the production function and is extremely important in a country's economic growth (1). The so-called low-carbon economy (LCE) strictly controls the consumption of traditional high-CO_2 emission and high-pollution energy such as coal and oil utilizing introducing new technologies and developing new power under the guidance of the scientific outlook on development and sustainable development (SD). This can curb greenhouse gas (GHG) emissions to a certain extent, make a favorable balance between economic progress, energy consumption, and environmental protection, thus achieving a social form of fast economic growth without sacrificing the environment, and finally realizing the optimization and upgrading of industrial structure and energy structure (2).

Many domestic and international researchers have studied the relevant aspects of talent policy. Combined with the characteristics of talent resource allocation in higher vocational colleges, Cui (3) analyzed the current situation of talent recruitment in China's vocational colleges to better complete the construction of the national "Double High-levels Plan" and improve the ability of these colleges to cultivate more outstanding talents for the society (3). Gao et al. (4) analyzed the problems existing in environmental accounting information exposure (EAIE) of agricultural and animal husbandry enterprises under LCE. They got a clearer understanding of this aspect, which is conducive to fundamentally proposing countermeasures to improve the level of EAIE (4). Xinsheng et al. (5) took China's rural areas as the research object, explored the status quo of the development of rural personnel, discussed the existing problems in the development of rural human resources, and put forward effective measures to revitalize rural talents, which provided a solid theoretical basis for better rural development (5). Allotey et al. (6) surveyed 10 math and science teachers about their beliefs about talent and their proposed strategies for developing gifted students into skills. The findings suggested that it is necessary to formulate a formal policy on S&T talent education and implement a teacher education plan to solve teachers' beliefs and knowledge about gift and talent education strategy (6). Marco and Lorenzo (7) investigated how promotion incentives affect the productivity of many highly skilled employees by using the three bibliometric thresholds of the national scientific qualifications in the centralized evaluation process of professional development of Italian universities. The results highlighted the importance of promotion incentives as practical motivational tools for public universities and general public organizations (7). From the point of view of theoretical research, foreign scholars have conducted earlier research on S&T talents policy, which mainly starts from education. Chinese scholars pay more attention to the overall grasp of S&T talents policy and advocate establishing the policy system.

Firstly, from the cultivation, evaluation, flow, and incentive of four aspects of S&T talents, the incentive and optimization policy of the skills are studied, and practical suggestions are raised. Secondly, a Chinese LCE optimization model is established to solve the economic output of each industry in the expected year. Finally, the CO_2 emission influence and output influence of each industry are analyzed. The results reveal that the energy sector is in the middle of the industrial chain and is the pillar industry of the national economy. Still, it is also the primary source of increasing CO_2 emissions. Some other sectors, such as the equipment manufacturing industry, are located in the lower part of the industrial chain and have a high driving effect on the economy. The innovation of this study lies in the optimization and adjustment of the structure of the industrial sector from the perspective of total carbon emission and total energy consumption control, aiming at the maximization of economic output, the minimization of CO_2 emission, and the assessment of industrial environmental efficiency, which provides the scientific basis and reference for how to upgrade the industrial structure and how to transition from the traditional economy to the LCE.

2. Optimization and incentive of S&T talents policy and low-carbon economy analysis method

2.1. Classification of S&T talents incentive policies

S&T talents policy involves a variety of contents, including the incentive, the use, management, and development of S&T talents, etc. In this study, the S&T talents policy is divided into four types, as displayed in Figure 1.

The S&T talents policy can be divided into four types: the flow, cultivation, incentive, and evaluation policy of S&T talents.

2.1.1. The flow policy of S&T talents

The flow of S&T talents mainly covers their introduction and a series of measures to regulate the introduction of relevant skills (8). The introduction policy of S&T talents is aimed at introducing technology personnel, and its principal contents are encouragement, service, support, and management (9). To sum up, the introduction policy of S&T talents refers to the normative criteria for the introduction of relevant skills to meet the needs of local social development under the background of national laws, regulations, and applicable policies to attract and introduce talents (10).

2.1.2. The cultivation policy of S&T talents

As the primary productive force, S&T plays an increasingly prominent role and position in society, and S&T talents, as its primary carrier, have become strategic elements of regional development (11). The relevant policy environment influences the cultivation effect of S&T skills. Scientific talent policy is beneficial to the better development of S&T talents. In summary, the cultivation policy of S&T talents stands for the personnel training program formulated to achieve the talents cultivation goal in a specific professional field. The S&T talent cultivation goal is achieved by standardizing talent cultivation behavior (12).

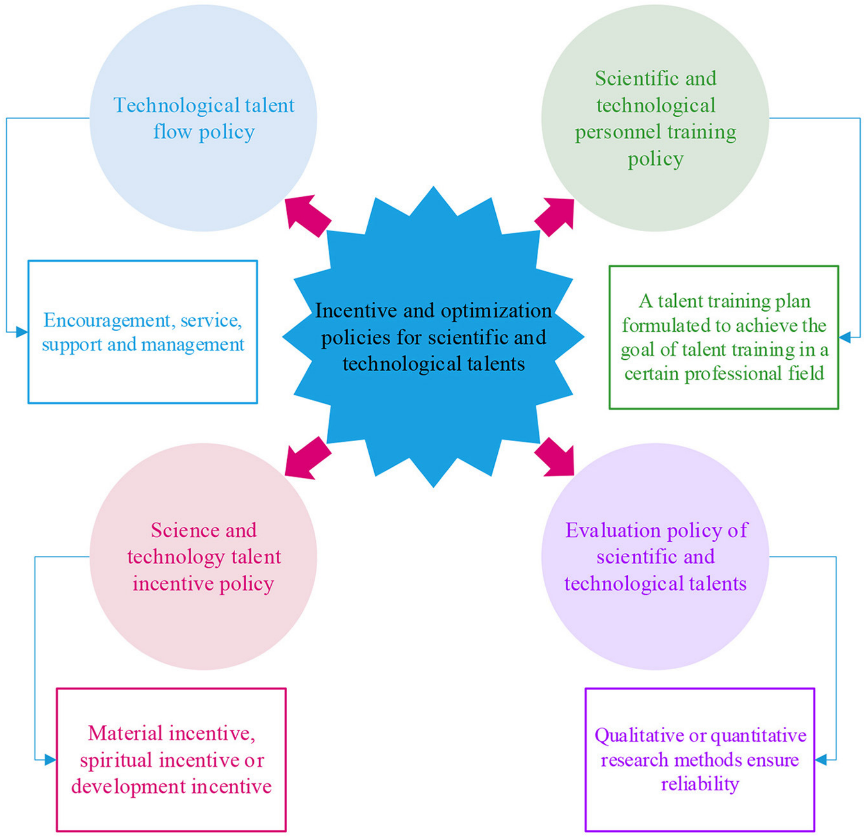

FIGURE 1
Classification of the S&T talents policy.

2.1.3. The incentive policy of S&T talents

It refers to the policy promoting S&T talents' working enthusiasm through spiritual, material, or development incentives (13). The spiritual incentive policy of S&T talents is to inspire these talents by maintaining the skills emotionally and recognizing their achievements. By providing convenience and assistance to S&T talents and their families to solve the concerns of these talents in addition to work, the motivation of such skills can be realized (14). The formulation of the S&T talents incentive policy should not only satisfy the demands of the talents maternally but also pay more attention to their spiritual and future development demands (15).

2.1.4. The evaluation policy of S&T talents

The evaluation mechanism of the S&T talents evaluation policy is indicated in Figure 2.

Because a complete cycle can fully reflect the situation of evaluation objects, the evaluation of S&T talents evaluation policy given PH should be carried out in an appropriate and complete cycle (16). The object of evaluation is the provider of evaluation information, which should be composed of members of government, enterprise, and university organizations (17). The evaluation subject should be selected randomly to ensure the objectivity of the evaluation result. The organizational preparation is mainly to prepare for the evaluation of the S&T talents policy (18). The implementation of policy evaluation is to ensure the scientific nature and reliability of the results of the S&T talents evaluation policy from the perspective of PH through qualitative or quantitative research methods so that the evaluation results become an essential basis for optimizing this policy from the point of PH (19). The feedback mechanism of the S&T talents evaluation policy is demonstrated in Figure 3.

From a PH perspective, the evaluation policies of S&T skills would be incomplete without a feedback mechanism. In this perspective, the policy optimization should not only be based on the feedback of the policy evaluation but also on listening to the opinions of the people who implement the policy. Based on the interests of the people, by building a policy information feedback platform, more people can have the opportunity to participate in the process of information feedback on this policy from the viewpoint of PH, to realize the innovation of the existing policy feedback mechanism from relevant perspectives.

2.2. The establishment of the low-carbon economy optimization model

The economic output is taken as the decision variable of the LCE optimization model, and the maximum economic output is chosen as the target variable of this model. CO_2 emission,

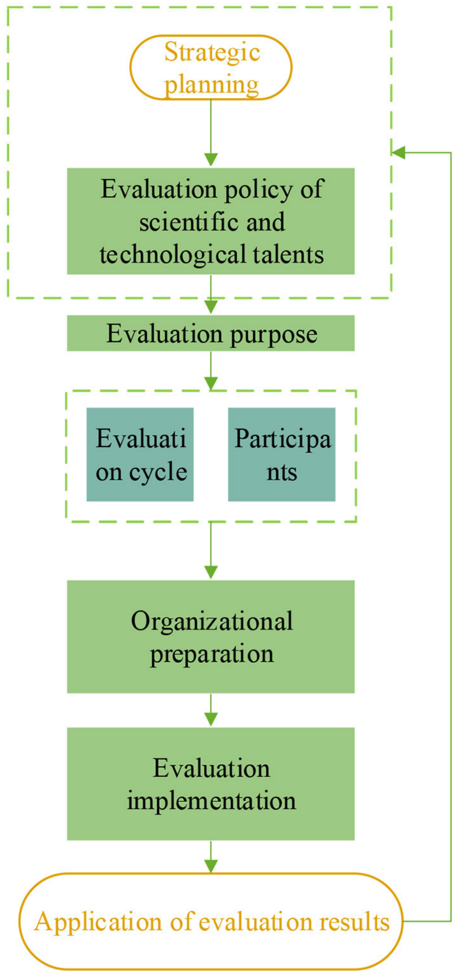

FIGURE 2
The evaluation mechanism of the evaluation policy of S&T talents.

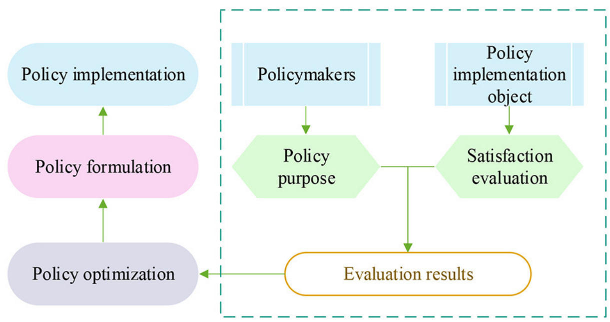

FIGURE 3
The feedback mechanism of the evaluation policy of S&T talents.

energy consumption, and economic output structures are selected as constraint conditions to solve the optimization model (20). In this section, the economic output of various sectors in China is taken as the decision variable of the optimization model, and the planning model is constructed to maximize the total economic output. Here, this study puts the control of carbon emission into the constraint to ensure the convenience of solving the model. Then, with energy consumption structure, CO_2 emission structure, and economic output structure as constraints, the general linear programming method is used to solve the optimization model. The solution method is the Simplex method and interior method. The model constructs the internal connection among economic growth, energy consumption, and CO_2 emission in an intuitive way. By adjusting the economic output of 41 national economy departments, the model finds the optimal output scheme in China based on controlling the total energy consumption and total carbon emission.

2.2.1. The setting of the objective function

The expression of the objective function of the optimization problem is as follows:

$$\max Z = i^T x = x_1 + x_2 + \ldots + x_{41} \quad (1)$$

x refers to the decision variable; x_j stands for the total output of department j according to the input–output table, $j = 1, 2, \ldots .41$; i signifies a scalar whose coefficients are all 1, $i = [1, 1, \ldots, 1]^T$. The objective function Z is to all of China's output of 41 industries for aggregation, representing the maximization of the total output (21). The number and names of industries are exhibited in Table 1.

Table 1 details the 41 sectors, including agriculture, forestry, animal husbandry and fishery, coal mining and washing industry, oil and gas mining, metal mining and non-metal mining, etc.

The calculation of carbon emissions mainly uses Equation (2):

$$E = AD * EF \quad (2)$$

AD refers to the consumption of fossil fuels, the use of raw materials, and the electricity purchased or exported in the production process during the accounting period. The unit of gas fuel is 10,000 cubic meters (104 m^3, standard state), and the unit of solid or liquid fuel is tons (t). EF stands for the CO_2 factor, namely the CO_2 coefficient. The emission coefficient of each energy is calculated by the Intergovernmental Panel on Climate Change (IPCC) according to the calorific value of energy combustion, as denoted in Figure 4 (22).

Natural gas is measured in tons of CO_2/billion m^3. Everything else is tons of CO_2/million tons. In Figure 4, the emission coefficient of natural gas is 218,500 tons of CO_2/billion m^3, that of raw coal and gasoline is 20,600 tons of CO_2/million tons, and 30,000 tons of CO_2/million tons. The CO_2 emission coefficient of these significant energy sources can be used to calculate the CO_2 emission influence of each industry.

2.2.2. Setting of constraint condition

The set classification of constraint conditions is revealed in Figure 5.

2.2.2.1. Total energy consumption constraint

This constraint represents the sum of all energy consumed by production activities in all departments, which does not

TABLE 1 The number and names of industries.

Number	Department name	Number	Department name	Number	Department name
1	Agriculture, forestry, animal husbandry, and fishery	15	Metal products industry	29	Wholesale and retail
2	Coal mining and washing industry	16	General and special equipment manufacturing	30	Accommodation and catering industry
3	Oil and gas extraction industry	17	Transportation equipment manufacturing	31	Financial industry
4	Metal mining and dressing industry	18	Electrical machinery and equipment manufacturing	32	Real estate industry
5	Non-metallic and other mineral mining and dressing industry	19	Communication equipment, computer, and other electronic equipment manufacturing industry	33	Leasing and business services
6	Food manufacturing and tobacco processing industry	20	Instruments and apparatuses	34	Research and experimental development industry
7	Textile industry	21	Crafts and other manufacturing industries (including waste)	35	Comprehensive technical service industry
8	Textile, clothing, shoes, hats, leather, down, and its products	22	Power and heat production and supply industry	36	Water conservancy, environment, and public facilities management
9	Wood processing and furniture manufacturing	23	Gas production and supply industry	37	Resident services and other services
10	Paper printing and cultural, educational, and sports goods manufacturing	24	Water production and supply industry	38	Education
11	Petroleum processing, coking, and nuclear fuel processing industry	25	Construction industry	39	Health, social security, and social welfare industry
12	Chemical industry	26	Transportation and warehousing	40	Culture, sports, and entertainment
13	Non-metallic mineral products industry	27	Postal industry	41	Public management and social organizations
14	Metal smelting and rolling processing industry	28	Information transmission, computer services and software		

exceed the established predicted value (23). It is expressed by Equation (2):

$$i^T A_e x \leq e_f \tag{3}$$

$A_e = diag(\beta^T E)$. E means the department's direct energy consumption coefficient matrix; β refers to the conversion coefficient of each energy into standard coal, as outlined in Table 2. $\beta^T E$ represents the total specific energy consumption produced by each department, namely, the comprehensive energy productivity, which is 1×41 matrix; e_f stands for the predicted energy expenditure of China in 2023 (24). Table 2 presents the energy conversion coefficient.

2.2.2.2. CO_2 emission constraint

The constraint refers to the sum of CO_2 emissions from production activities of all sectors, which does not exceed the established predicted value (25), as defined in Equation (3):

$$i^T A_c x \leq c_f \tag{4}$$

$A_c = diag(i^T C)$. C indicates the direct CO_2 matrix; $i^T C$ represents the total amount of CO_2 consumed by each department's production unit output, which is also a 1×41 matrix (26). c_f signifies the predicted total CO_2 emissions of China in 2023.

2.2.2.3. Economic development level constraints

This constraint expresses the sum of the added value of all sectors so that the total amount is not lower than the set forecast of Gross Domestic Product (GDP) (27). The economic development level constraint is written as Equation (4):

$$i^T (I - A) x \geq y_f \tag{5}$$

A means the coefficient matrix of the intermediate consumption of the department; I is the identity matrix of 41×41; $I - A$ displays the value-added coefficient matrix; y_f denotes the predicted total GDP of China in 2023.

2.2.2.4. Constraints on the scope of departmental restructuring

It can be represented in Equation (5):

$$lb_j \leq x_f \leq ub_j, j = R^{41} \tag{6}$$

lb_j and ub_j express the lower and upper bound of the output of department j (28). In addition, another purpose of adding this

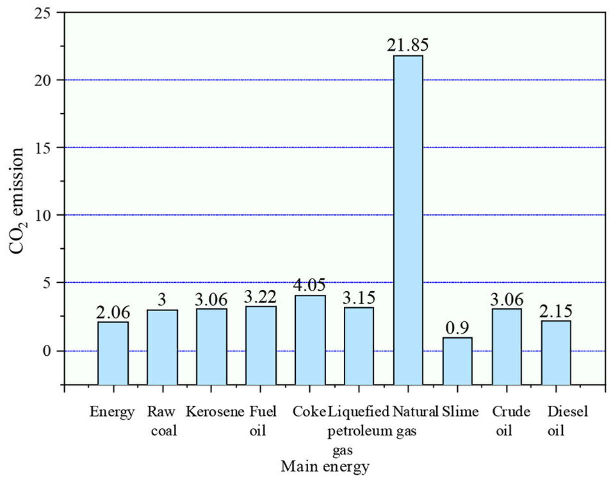

FIGURE 4
The emission coefficient of the primary energy CO_2.

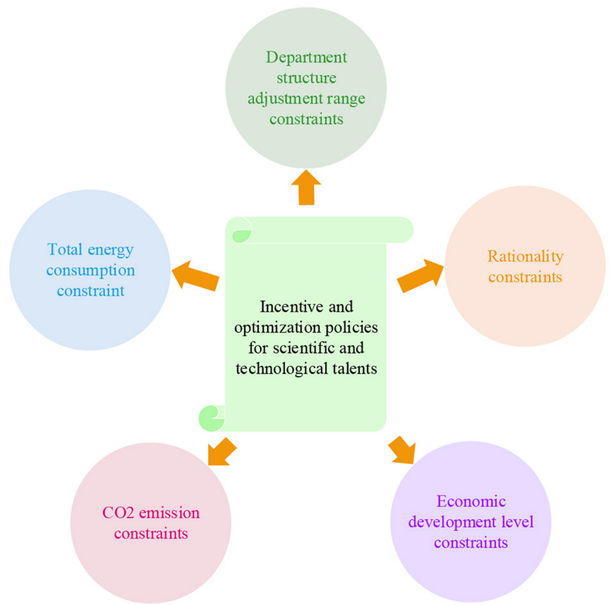

FIGURE 5
Setting of constraint condition.

constraint is to eliminate the extreme conditions in the feasible solution set.

2.2.2.5. Rationality constraint

$$x_j \geq 0, j = 1, 2, \ldots, 41 \tag{7}$$

$x_j \geq 0$ means that the output of all departments must be non-negative.

TABLE 2 Conversion coefficient of energy.

Name	Conversion factor
Coal	0.7144
Coke	0.9715
Crude oil	1.4288
Gasoline	1.4711
Kerosene	1.4714
Diesel oil	1.4570
Fuel oil	1.4285
Natural gas	13.23
Power	1.230

2.2.3. Stationarity test

Generally, the method to test the stationarity of sequence is the Unit root test. In this study, the traditional Augmented Dickey-Fuller (ADF) test and Kommunisticheskaya Partiya Sovetskovo Soyuza (KPSS) test are principally used to ensure the accuracy of the results (29).

2.2.3.1. ADF test

ADF test is based on the Dickey and Fuller (DF) test to expand, its core problem is to test whether the slope coefficient ρ in Equation (7) is 1.

$$Dx_t = \alpha + \rho x_{t-1} + \varepsilon_t \tag{8}$$

D represents the difference factor; $\{\varepsilon_t\}$ is a white noise sequence with a mean value of 0, a variance of σ^2, and an Identical Independent Distribution.

The original hypothesis H0 of the ADF test is that the sequence $\{x_t\}$ has a unit root, that is $\rho = 1$, that is, $\{x_t\}$ is a non-stationary sequence (30). It is assumed that the value of the characteristic root P is within the unit circle and the sequence is stable. According to tradition, the statistics constructed are:

$$t = {}^{(\hat{\rho}-\rho)}\!/_{se(\hat{\rho})} \tag{9}$$

$\hat{\rho}$ is the estimated value of the parameter ρ obtained by ρ using the Ordinary Least Squares (OLS).

Under the original assumption, the limiting distribution of the statistic t still obeys the general Gaussian distribution. Still, the convergence rate of the intercept term and the slope term is different.

$$\begin{bmatrix} T^{1/2}(\hat{\alpha}-\alpha) \\ T^{3/2}(\hat{\rho}-1) \end{bmatrix} \rightarrow N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \sigma^2 \begin{bmatrix} 1 & \alpha/2 \\ \alpha/2 & \alpha^2/3 \end{bmatrix}^{-1}\right) \tag{10}$$

Under the alternative hypothesis, regardless of $\rho = 0$ or $|\rho| < 1$, The limit distribution of the statistic t is still standard normal.

When the equation contains lagging items of Dx_t, Equation (6) needs to be rewritten as:

$$Dx_t = \alpha + \rho x_{t-1} + \sum_{i=1}^{\rho} \beta_i Dx_{t-i} + \varepsilon_t \quad (11)$$

2.2.3.2. KPSS test

KPSS test is proposed based on the idea of the traditional hypothesis test. In any hypothesis test, there are two kinds of errors: "false rejection" (Class I error) and "false taking" (Class II error). Based on the original assumption of serial stability, Lagrange Multiplier (LM) statistics can be obtained by the general estimation method.

$$LM = \sum_{t=1}^{T} S_t^2 / \hat{\sigma}_e^2 \quad (12)$$

$$S_t = \sum_{t=1}^{T} e_t \quad (13)$$

$$\hat{\sigma}_e^2 = \sum_{t=1}^{T} e_t^2 / T \quad (14)$$

e is the estimate of the residual term ε_t in Equation (7). Of course, if there is a sequence correlation in the residual term, that is, the covariance matrix is not an identity matrix, then:

$$\hat{\sigma}_e^2 = \sum_{t=1}^{T} e_t^2 / T + 2 \sum_{t=s+1}^{T} w(.)\, e_t e_{t-s} / T \quad (15)$$

$w(.)$ stands for variable-weight functions, and various kernel functions choose different smooth ways.

ADF and KPSS methods are employed to test the stationarity of the three sequences. The results of the two tests are compared in Table 3. Among them, the Autocorrelation function (ACF) lag order is selected by minimizing the Schwarz Information Criteria (SIC) criterion, and the intercept term is used as an exogenous variable.

In Table 3, ADF inspection considers that the sequence of GDP, energy consumption, and CO_2 emissions after logarithmic treatment is a non-stationary I(1) process. All three become stationary processes after first-order differences. KPSS inspection considers that no matter which variable, its original sequence after logarithmic is non-stationary, and after first-order difference, the three sequences become stationary. Therefore, all three variables can be considered as I(1) processes.

TABLE 3 Test results for stationarity.

Variable name	ADF inspection		KPSS inspection	
	Original sequence	After first-order difference	Original sequence	After first-order difference
Ln (GDP)	−1.82	−5.52	0.2	0.097
	(0.68)	(0.001)***	(0.03)***	(0.15)
Ln (Energy)	−1.41	−4.46	3.01	0.1402
	(0.59)	(0.001)***	(0.01)***	(0.13)
Ln (CE)	−1.35	−4.53	3.0003	0.1355
	(0.608)	(0.001)***	(0.01)***	(0.16)

[a]The lag order of the ADF test is selected as 3; the KPSS test truncation lag variable is 1.
[b]** and*** represent the statistically exact number at 5% and 1%, respectively.

3. Experimental design and performance evaluation

3.1. Recommendations for optimizing S&T talents policy from a PH perspective

In the view of PH, the recommendations for optimizing the S&T talents policy are plotted in Figure 6.

This study puts forward some suggestions on S&T talents policy from the viewpoint of optimizing PH. It mainly covers establishing a complete policy system, expanding policy coverage, strict implementation of such talent evaluation policy, and improving the guarantee mechanism of the talent introduction policy. Establishing a complete policy system includes clarifying the main body of the policy-making and optimizing the structure of this policy. The expansion of policy coverage includes paying attention to the role of such talents at all levels, implementing the training plan for young scientists, and implementing the S&T talents continuing education project. The strict implementation of the S&T talents evaluation policy involves increasing the publicity and establishing the evaluation mechanism and feedback mechanism of the policy.

3.2. Solution of low-carbon economy optimization model in China

Matlab has powerful data processing and analysis functions. This study adopts Matlab software to solve the economic output of each department in the expected year, and the overall economic indicators in 2017 and 2022 are obtained, as illustrated in Figure 7.

In 2017, the proportion of agriculture, forestry, animal husbandry, and fishery in the primary industry was 5.33%, that of energy in the secondary sector was 72.04%, and that of

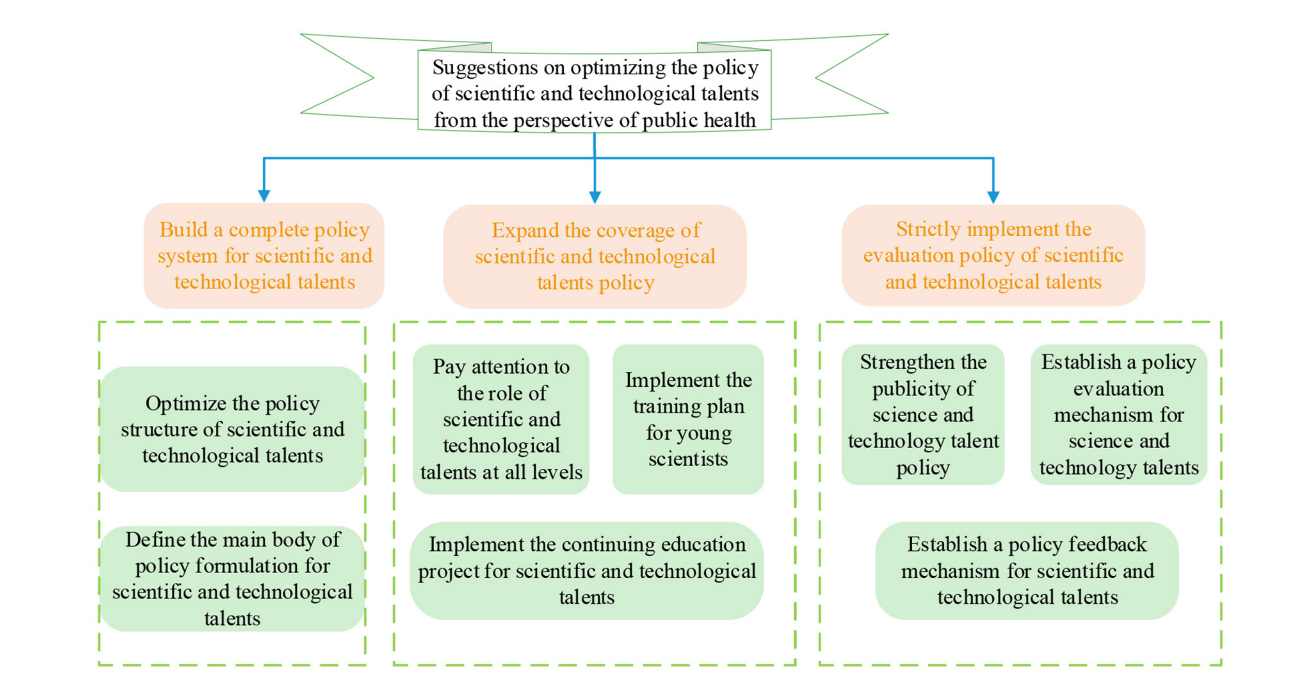

FIGURE 6
The suggestions for optimizing the S&T talents policy.

service in the tertiary industry was 22.63%. In 2022, the primary, secondary, and tertiary industries accounted for 6.09%, 68.44%, and 25.47%. The proportion of the primary sector in the overall economy did not change much. The economic added value and the total output of China's three major industries are presented in Figure 8.

Compared with 2017 (base year), the total economic added value of the three industries reached 61.5 trillion yuan, 15.6 trillion yuan more than that of 2017, the total economic output value of the three sectors achieved 184.8 trillion yuan, 44.19 trillion yuan more than that of 2017. The declining trend of the output of the secondary sector is evident, illustrating that the constraints of energy conservation and emission reduction impact the industrial sector as a whole. The proportion of tertiary industry increased slightly.

3.3. Analysis of the influence coefficient of various departments

3.3.1. Industrial influence coefficient

The industrial influence coefficient from 2016 to 2022 is signified in Figure 9.

The industrial influence coefficient of all sectors in China during 2016–2022 is stable. The influence coefficient of the secondary industry is much higher than that of the primary and tertiary industries as a whole, and most of them are more than the average value of social industries. Thus, it can be found that the secondary sector is still the main driving force of the national economy in China. Among them, the driving effect of agriculture, forestry, animal husbandry, and fishery on China's economy has been declining yearly, with the influence coefficient dropping from 1.15 in 2016 to 0.67 in 2022. In addition to transportation and storage, the industrial influence coefficient of other departments of the tertiary industry is generally lower than the average level of the national economy. Besides, the driving capacity of the transportation industry for the overall economy also presents a downward trend year after year, from 1.35 in 2016 to 0.97 in 2022. It indicates that the service industry plays an insignificant role in driving China's overall economy. In the manufacturing industry, the chemical industry, metal smelting, and calendering industry have the strongest pulling force, with an average influence of more than 2 in 2016–2022. While light manufacturing industries, such as textiles, wood processing, and furniture manufacturing, have a low pull on the overall economy and a downward trend. Among the products and services of the mining industry, the industrial influence of all four sectors was low, maintaining around 0.5 between 2016 and 2022.

3.3.2. The influence coefficient of CO_2 emission

The influence coefficient of CO_2 emission during 2016–2022 is portrayed in Figure 10.

During 2016–2022, except for a few sectors, the amount of CO_2 emitted per unit of the added value of all industries in China appeared a downward trend, which means that the carbon productivity of each sector increased with each passing year, illustrating that the "low carbon development" trend of China's economy is generally good. In terms of industrial influence and

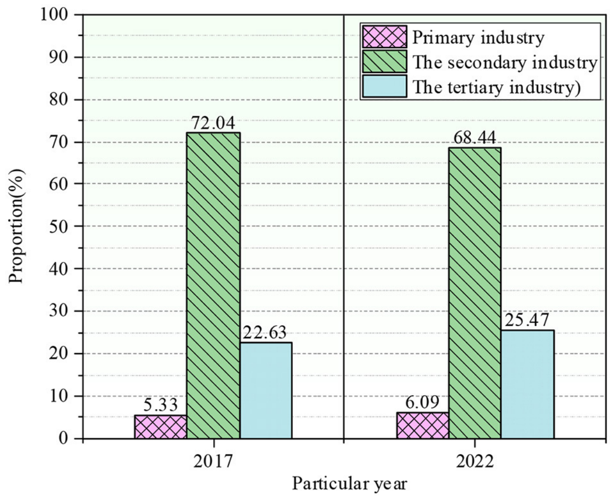

FIGURE 7
Overall economic indicators for 2017 and 2022.

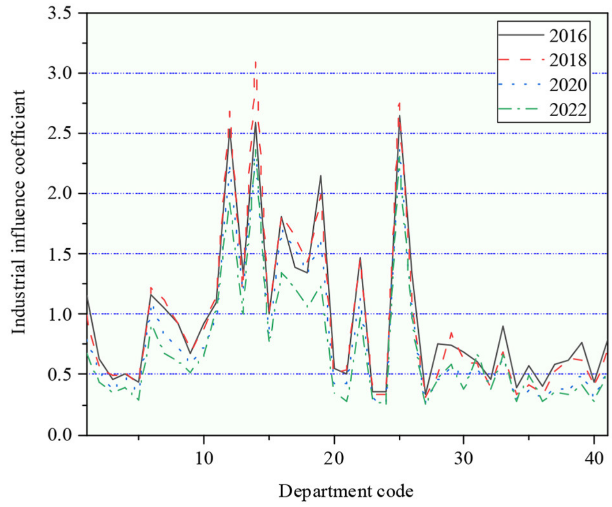

FIGURE 9
The industrial influence coefficient during 2016–2022.

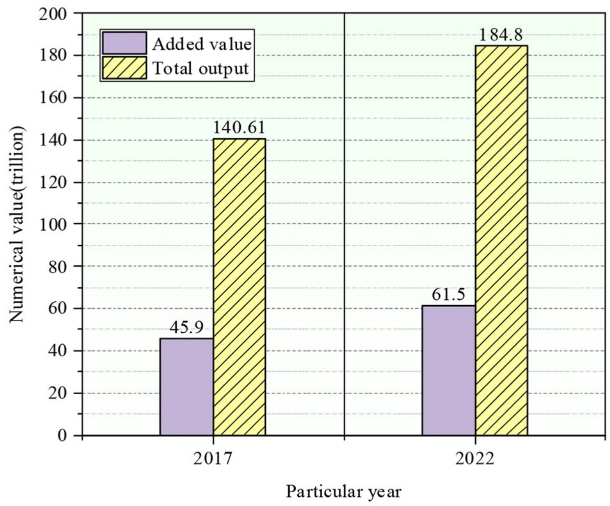

FIGURE 8
The added value and a total output of the three industries.

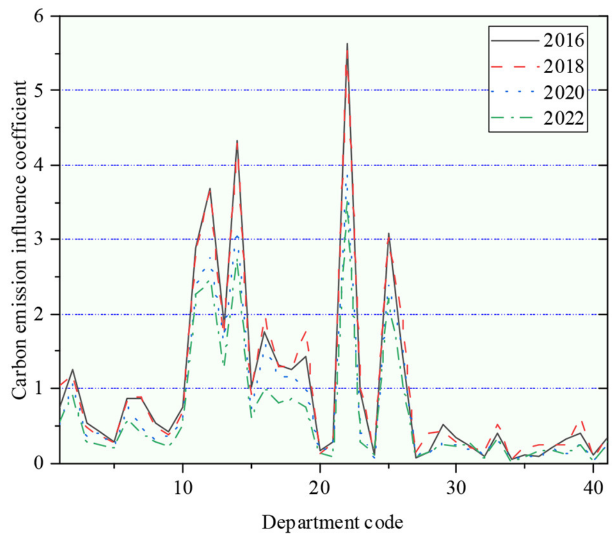

FIGURE 10
The influence coefficient of CO_2 emission from 2016 to 2022.

CO_2 emission influence, the driving role of the secondary industry is much higher than that of the tertiary and primary industries, and most of them are resource-intensive industries. However, the effect of the tertiary industry on the overall economy has gradually emerged and expanded. In conclusion, the secondary industry will remain a pillar industry in China during the 2016–2022 period. But in terms of trends, the influence of services has risen slightly over this period, while manufacturing has tended to decline. By comprehensively considering the CO_2 emission and industrial influence coefficients, China should give priority to developing industries with low carbon influence. The scientific development of these sectors with high carbon emissions and high industrial impact has been promoted, mainly through technological improvement to reduce and limit high CO_2 emissions of these industries.

4. Discussion

The first section is the countermeasures and proposals of S&T talents policy from the perspective of optimizing PH. There are four significant countermeasures, namely, the establishment of the S&T talents policy system, the expansion of coverage groups, the implementation of evaluation policies, and the improvement of the introduction of safeguards, each deepens the strategies of two to three minor aspects, respectively. In the second section, by solving the LCE optimization model of China, it is concluded that the proportion of agriculture, forestry, animal husbandry, and fishery in the overall economy has little change. In contrast, the output of the secondary industry has a relatively obvious downward trend, showing that the constraints of energy conservation and emission reduction have an influence on the industrial sector. In the third section, through the analysis of the influence coefficient of various industries, the industrial influence coefficient of all sectors in China during 2016–2022 is stable. Generally, the influence coefficient of the secondary sector is much higher than that of the primary and tertiary industries, and most of them override the average value of social industries. Thereby, it can be drawn that the secondary sector is still the main driving force of the national economy. Liu et al. (31) implemented an energy-saving and emission-reduction decision optimization model from the perspective of a low-carbon supply chain of auto parts (31). Compared with this study, it can be studied from the standpoint of energy conservation and emission reduction and added the perspective of industrial influence.

5. Conclusion

The direct purpose of LCE is to reduce emissions of CO_2 and other GHGs under the premise of ensuring a certain economic growth rate. Its essence is to optimize the industrial structure, improve energy efficiency, and achieve the goal of low-carbon development. China is currently facing multiple challenges such as improving people's quality of life, stabilizing economic growth, and limiting the total amount of CO_2 emissions. S&T talents incentive policy has vital theoretical value and practical significance for China to realize the transformation of LCE and SD. Firstly, from four aspects of S&T talents evaluation flow, cultivation, and incentive of S&T talents, the study explores incentive and optimization of the S&T talents policy and puts forward effective suggestions. Secondly, a Chinese LCE optimization model is constructed. Using MATLAB software, the economic output of each sector in the expected year can be solved to obtain overall economic indicators for 2017 and 2022. Finally, the output influence of each industry and CO_2 influence are analyzed. The results of the study are as follows: (1) From the point of view of PH, the suggestions and countermeasures of the S&T talents policy mainly consist of four parts: expanding the coverage group of this policy, establishing a complete policy system, perfecting the safeguard mechanism of such talents introduction policy, and strictly implementing these talents evaluation policy. (2) Compared with 2017, the total economic output of the three industries reached 184.8 trillion yuan, 44.19 trillion yuan higher than that of 2017. (3) Overall, the influence coefficient of the secondary industry is much stronger than that of the primary and tertiary sectors, and the majority exceed the mean value of social industries. Consequently, it can be concluded that the secondary industry is still the main driving force of the national economy in China. The disadvantage is that in the comparable price input–output model used in this study, the price deflator of the tertiary sector is determined by the added value coefficient. Due to data limitations, the added value coefficient in the statistical yearbook cannot cover all sectors. Thus, the added value coefficient of other service industries is used to deflate the remaining industries, which will slightly affect the accuracy of the data. Besides, price factors such as carbon prices and policy trends of various provinces need to be incorporated into the relevant influencing factors in the study content, so as to achieve a more complete development strategy for China's LCE. Therefore, in future studies, the regional development trend of China's LCE will be tracked timely according to the update of data, and the future growth trend will be predicted as far as possible by using rigorous and scientific models based on relevant statistical methods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Northeastern University Ethics Committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Optimal utilization of ecological economic resources and low-carbon economic analysis from the perspective of Public Health

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Introduction: China's urbanization process continues to deepen with social development, but the optimal utilization of ecological, economic resources and Public Health (PH) problems are becoming increasingly severe.

Methods: This paper analyses the optimal use of urban resources based on PH. Here, the public space of urban settlements is selected as the research object. Firstly, the connotation and essence of the ecological economy and Low-Carbon Economy (LCE) are analyzed. Secondly, the characteristics of public space in urban settlements are studied based on PH. The public space satisfaction evaluation model in urban settlements is constructed with five first-level and 12 second-level indicators. Finally, a questionnaire is designed to analyze urban households' outdoor activities and evaluate public space in settlements.

Results: The influencing factors of residents' satisfaction with public space in settlements are obtained through regression analysis. The results show that residents' satisfaction with the public space of the settlement is mainly evaluated from three aspects: the accessibility of public space, the integrity of public space, and the pleasure of public space. The influence coefficients are 0.355, 0.346, and 0.223, respectively, indicating that the influence degree of the three principal factors decreases in turn.

Conclusion: We can optimize the utilization of urban residential public space resources from the aspects of accessibility, integrity and pleasure, so as to promote residents to go to public spaces for outdoor activities and physical exercise, which is more conducive to the public health of residents.

KEYWORDS

Public Health, ecological economy, Low-Carbon Economy, public spaces in settlements, satisfaction evaluation indicators

1. Introduction

With the continuous progress of Chinese society, urbanization is also deepening. The focus of urban problems has shifted from focusing on static physical space problems to emotional behavioral, social, temporal and spatial issues. This is followed by a contradiction between the growing needs of residents and the physical spatial environment (1). Therefore, it is essential to study the interaction between Public Health (PH) status and specific spaces that affect health activities, which is one of the characteristics of the quality of life of urban residents. Studies in recent years have shown that China's PH problems have gradually shifted to chronic diseases, sub-health, and sudden infectious diseases. Regular outdoor activities can improve PH and reduce disease risk (2).

The issuance of relevant national documents on the construction of ecological civilization puts forward higher requirements for protecting regional ecological security, optimizing the pattern of spatial development, and protecting and expanding ecological space. The concept of the Low-Carbon Economy (LCE) and ecological economy also means that building an ecological civilization, improving the ecological environment, and promoting green development have become the country's strategic needs in the new era. As the world's largest developing country, China is responsible for reducing carbon emissions and developing an ecological economy (3, 4). LCE can promote the protection and recycling of the ecological environment. A green ecological environment can make people's physical and mental health develop slowly in a positive direction, which is more conducive to PH. Therefore, exploring the optimization and utilization of resources suitable for China's ecological and LCE and achieving sustainable economic and social development is of great practical significance.

Based on this, this paper takes the public space of urban settlements as the research object. It analyzes the characteristics of public space in urban settlements from the perspective of PH from the relevant theories of the ecological economy and LCE. Besides, the evaluation model of public space satisfaction in urban settlements is constructed. The research data are obtained through the questionnaire survey. The data are analyzed by Multiple Linear Regression (MLR) to get the influencing factors affecting residents' outdoor activities in public spaces. The research on the evaluation indicator of public space in urban settlements can provide a theoretical basis for the optimal utilization of public space resources under the ecological economy. The structure of this paper can be divided into the following sections. Section 1 is the introduction that mainly introduces the research's background, purpose, and significance. Section 2 is a literature review. The main questions are raised. Section 3 is the research methodology. It introduces the theoretical foundations used here, such as ecological economy, LCE, PH, and urban public space. The satisfaction evaluation model of public space in settlements is constructed based on the characteristics of public space in urban settlements. Section 4 is experimental design and result analysis. The survey results are obtained by studying the data from the questionnaire by analyzing the source of the data and linear regression. It is compared with similar studies to confirm the correctness of the results. Section 5 is the conclusion that summarizes the results and draws conclusions and the implications and prospects for future research.

2. Literature review

Scholars have done much research on public spaces in urban settlements. Shojai and Fattahi explored urban design issues at the micro-urban design level. A comparison was made between Shiraz, Iran, and Sapporo, Japan. They used social psychology methods to study the similarities and differences in the arrangement of open spaces in contemporary settlements (5). Abdallah and Mahmoud aimed to evaluate and improve the thermal comfort of open spaces and the thermal perception of residents in the urban residential community of New Asyut City, Egypt. They assessed the thermal conditions of the periphery of urban residential communities using six design scenarios. It was concluded that increasing tree density and semi-shade in open spaces between residential buildings could increase the external environmental benefits of residents of new urban residential communities in hot arid climates (6). Lai et al. comprehensively reviewed current outdoor thermal comfort research, including outdoor thermal comfort benchmarks, data collection methods, and models. A conceptual framework was proposed. Physical, physiological, and psychological factors acted as direct effects. Behavioral, personal, social, and cultural factors and hot history, places, and allies were indirect influences. Then, these direct and indirect factors were decomposed and reviewed, and the interactions between various factors were discussed (7). Liang et al. proposed a new open-space simulation model using cellular automata. It allowed the spatial simulation of open spaces in urban areas to interact with urban dynamics. It was constrained by strategies to control different average sizes of open space in new urban areas. Walkability and population coverage were used to assess the effectiveness of creating new operating systems (8). Wei and Jones explored the emergence of urban agriculture and its changing nature and role in China's urbanization process. They cited a planned settlement in Kunming, Yunnan Province, as an example. The physical and spatial manifestations of urban farming practices and stakeholder motivations and attitudes were identified (9). For the outdoor thermal comfort and adaptive behavior in the edge season, Leng et al. selected three representative residential public open spaces in Harbin, a typical winter city, for empirical research. Meteorological measurements and basic questionnaires were conducted. Observations were made to explore outdoor thermal comfort and adaptive behavior (10).

The above studies analyze the public space of residential areas from the perspectives of residential area layout, thermal comfort of residential, public space, open space simulation, and outdoor thermal comfort. However, few studies are based on public space in settlements under PH and ecological economy. Therefore, this paper analyzes the satisfaction evaluation model of public space in urban settlements based on public space from ecological economy and LCE.

3. Research methodology

3.1. Analysis of ecological economy and LCE

Ecological economics is the study of the relationship between ecosystems and economic systems. It plays a vital role in many important issues facing human development today. The core of the study of ecological economics is the issue of sustainable development. The underlying idea is that the earth's economy is a material economy with a closed ecological loop (11). Based on the environmental economy, scholars also proposed the green economy, circular economy, and LCE. The green economy advocates the efficient and civilized use of natural resources based on social and ecological conditions. It is an "affordable economy" with an improved environment and promoted quality of life. Circular economy believes that economy and ecology are a closed-loop and recyclable system. An LCE is about saving energy while reducing greenhouse gas emissions, maintaining economic and

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TABLE 1 Comparison of ecological economy, green economy, circular economy, and LCE.

Conception	Ecological economy	Green economy	Circular economy	LCE
Time of presentation	Late 60s of the 20th century	In 1989	In 1990	In 2006
Theoretical basis	Ecology and economics	Environmental economics, sociology, ecology	Ecological economics	Energy economics
Purpose	Develop a sustainable economy and reduce environmental pollution	The healthy and harmonious development of human society	Build a resource recycling and efficient utilization system	Improve energy efficiency and reduce greenhouse gas emissions

social stability, and achieving sustainable development. LCE is developed based on the ecological economy, its ultimate goal (12). A comparison of the four economies is shown in Table 1 (13).

Regardless of the main problems these economies solve, their essence is to promote economic development, ecological protection, and social progress. The ultimate goal is to achieve sustainable development of human society (14).

3.2. Public spaces in urban settlements under PH

Health was initially considered and mechanically to be a state of "absence of disease and disability." With the development of medicine, the connotation of health is also gradually developing. The World Health Organization defines "health" as not simply the absence of any disease or infirmity of an individual but a state in which they adapt well to the society of this era at physical, mental, and social levels (15). PH refers to the overall health of the population. The collective health requires the coordination of defense mechanisms with the whole society. PH includes three aspects: physical, mental, and social health. Among them, physical health refers to the good physical fitness of residents, and there are no diseases. Mental health refers to residents' emotional and mental stability without negative emotions such as anxiety and depression. Social health is the harmonious and good interpersonal relationship generated by the interaction between the individual resident and the physical space environment and social environment (16).

Cities are where residents live and work, and settlements are relevant to everyone. The public space of the residential regions is an important material function space that carries residents' daily activities (17). The public space of urban settlements is the spatial carrier of residents' activities. Its core value is publicity. It includes physical space and a multi-level system consisting of functional facilities, green spaces, and traffic spaces. The public space of urban settlements is the generator of residents' daily life. It functions as a public service and public activity in settlements and provides residents with ubiquitous leisure spaces (18, 19). Public space in urban settlements needs to be well utilized as a spatial resource in the ecological and LCE. However, the rapid development of society has led to urban environmental pollution. The quality of the space deteriorates. The sedentary way of working of modern people leads to reduced physical activity. These create an imbalance between supply and demand (20). As a medium, the public space of urban settlements has the extroversion of communicating urban space and can carry the function of residents' daily life. It has the introversion of aggregating residents and neighbors. The main characteristics of public spaces in urban settlements are shown in Figure 1 (21, 22).

Figure 1 shows that public space in urban settlements has four characteristics: functional complexity, spatial accessibility, green ecology, and planning coordination (23, 24). First, residents' use of public spaces in settlements is often not limited to a single function. For example, parents will chat with neighbors while babysitting in the children's play space. Seniors will square dance on unused basketball courts, which requires the functional complexity of public spaces. Second, residents consider the accessibility of the space to decide whether to go to the space to participate in the activities they want to join. A high level of accessibility stimulates residents' initiative to engage in outdoor activities actively. Then, as the functional group of the smallest unit, the public space of urban settlements is the public space closest to the lives of residents. It is an integral part of the urban green ecological environment network to improve the green network and create a complete system. It has green ecology. Finally, promoting public space construction in urban settlements under the guidance of PH should form a systematic public space system which meets the overall principle of today's healthy city construction.

3.3. Satisfaction evaluation model of public space in settlements

Under the promotion of ecological economy and LCE, based on PH, the public space of urban settlements should use accessibility, safety, practicality, ecology, and pleasure as the main goals to construct a satisfaction evaluation model of public space in settlements. The details are revealed in Figure 2 (25).

In Figure 2, the satisfaction of public space in urban settlements is evaluated from five aspects: accessibility, safety, practicality, ecology, and pleasure. The specific criteria are: in the comprehensive evaluation of public space in urban settlements, accessibility includes Q1 walking distance time and Q2 road accessibility. Safety mainly includes Q3 night lighting quality, Q4 traffic diversion, and Q5 location. The practicality mainly includes Q6 the completeness of the types of public service facilities, Q7 the richness of the types of activities that the site can undertake, and Q8 the neatness of the ground paving. Ecology mainly includes Q9 space green viewing rate and Q10 space sunshine ventilation conditions. Pleasure mainly includes Q11

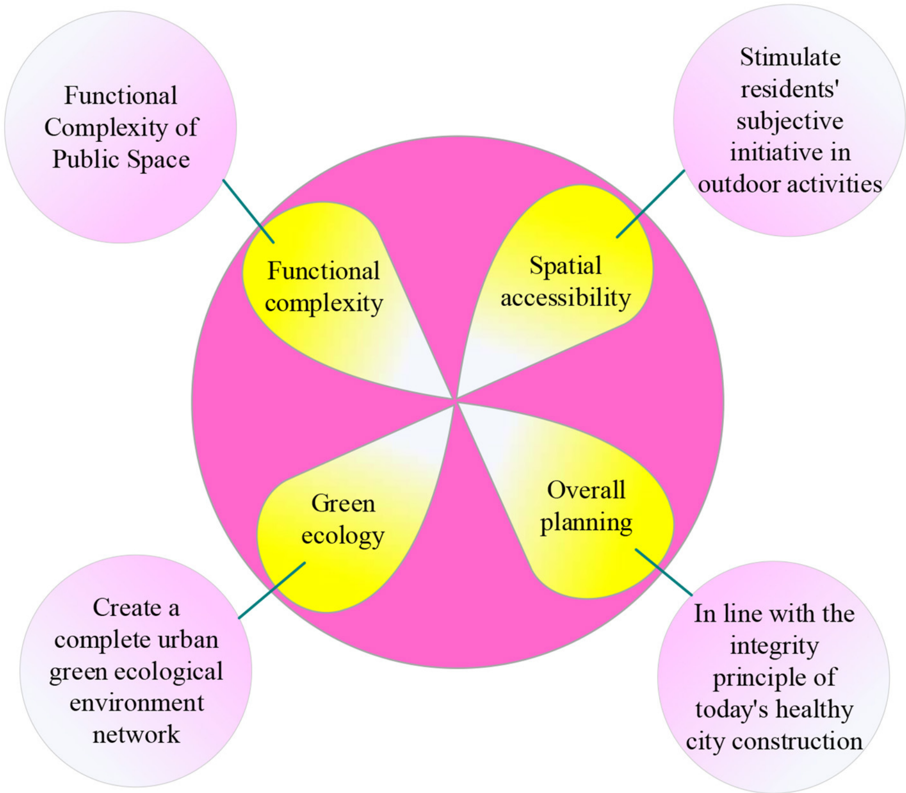

FIGURE 1
Characteristics of public space in urban settlements.

humanities education fun and Q12 neighborhood communication activities (26, 27).

MLR models are used for analysis. Suppose there is a linear correlation between the dependent variable Y and the l independent variable X. The model is (28):

$$Y = \gamma_0 + \gamma_1 X_1 + \gamma_2 X_2 + \cdots + \gamma_l X_l + \sigma \tag{1}$$

In Eq. (1), γ_0 is a regression constant. $\gamma_1, \gamma_2, \cdots, \gamma_l$ are regression coefficients. σ is the regression residual.

If m observations are made for the independent variable X and the dependent variable Y, the observations for the m group are obtained. Then, its matrix is:

$$\begin{cases} Y_1 = \gamma_0 + \gamma_1 X_{11} + \gamma_2 X_{12} + \cdots + \gamma_l X_{1l} + \sigma_1 \\ Y_2 = \gamma_0 + \gamma_1 X_{21} + \gamma_2 X_{22} + \cdots + \gamma_l X_{2l} + \sigma_2 \\ Y_m = \gamma_0 + \gamma_1 X_{m1} + \gamma_2 X_{m2} + \cdots + \gamma_l X_{ml} + \sigma_m \end{cases} \tag{2}$$

In Eq. (2), $\sigma_1, \sigma_2, \cdots, \sigma_m$ is the regression residual.

The questionnaire is conducted here. The reliability of the questionnaire is measured using a reliability factor, which is calculated according to Eq. (3).

$$\alpha = \frac{k}{k-1} * (1 - \frac{\sum_{i=1}^{k} S_i^2}{S_T^2}) \tag{3}$$

In Eq. (3), k is the total number of items in the questionnaire. S_i is the within-question variance of the score for the ith question. S_T is the variance of the total score for all questions. The reliability coefficient of the questionnaire should preferably be above 0.8, and between 0.7–0.8 is acceptable.

The Kaiser-Meyer-Olkin (KMO) test is used to verify the validity of the questionnaire. It is calculated according to Eq. (4).

$$KMO = \frac{\sum \sum_{i \neq j} r_{ij}^2}{\sum \sum_{i \neq j} r_{ij}^2 + \sum \sum_{i \neq j} r_{ij*1,2,\cdots,k}^2} \tag{4}$$

KMO metrics are as follows. Above 0.9 indicates that it is very suitable; 0.8 indicates that it is suitable; 0.7 means fair; 0.6 indicates that it is not very suitable; below 0.5 indicates that it is extremely unsuitable. The KMO statistic is between zero and one. When the sum of squares of the simple correlation coefficients between all variables is much greater than the sum of squares of the partial correlation coefficients, the KMO value is close to one. The closer the KMO value is to one, the stronger the correlation between the variables and the more suitable the original variable is for factor analysis. When the sum of squares of the simple correlation coefficients between all variables is close to zero, the closer the KMO value is to zero, the weaker the correlation between the variables, and the less suitable the original variables are for factor analysis.

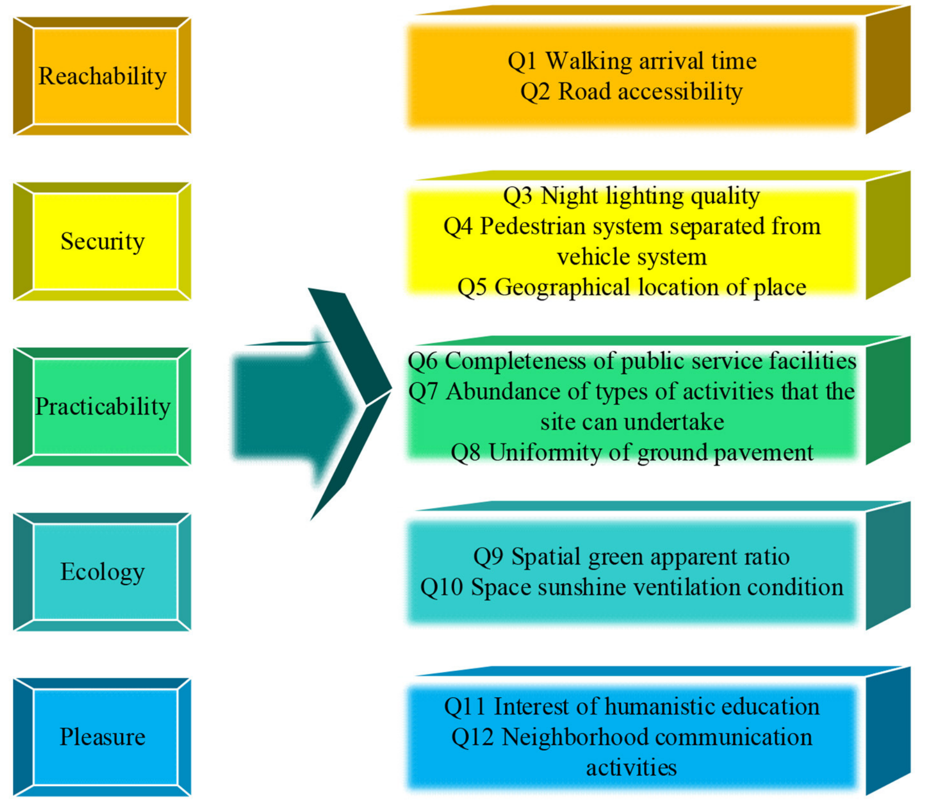

FIGURE 2
Evaluation model of public space satisfaction in urban settlements.

4. Experimental design and performance evaluation

4.1. Datasets collection

J City is selected as the research object. Settlement A was completed in 1994 with a total of 2,225 households. It is a multi-story building and is a first-class demonstration community for transforming the old city in China. Settlement B was completed in 2005 with a total of 4,129 households. It is a multi-high-rise building and is the first patented settlement in J City. Settlement C was completed in 1998 with a total of 1,943 households. It belongs to multi-story and multi-high-rise mixed buildings. It is also China's first batch of national healthy housing demonstration project communities. A random sample is taken here, and questionnaires are distributed to the selected A, B, and C settlements. Samples are performed for all ages and in clear and rainless weather.

The questionnaire is divided into three main parts. The first part is the basic information of the respondent, such as gender, age, educational background, and length of residence. The second part is the basic situation of outdoor activities, including the frequency of outdoor activities in the community and the time and duration of outdoor activities. The third part is the evaluation of the public space of the settlement, which is carried out from five aspects: accessibility, safety, practicality, ecology, and pleasure. There are 12 second-level indicators from Q1 to Q12. Each second-level indicator has a maximum score of five points, from high to low, five points for very satisfactory, four for more satisfactory, three for general satisfaction, two for less satisfactory, and one for very dissatisfied. Meanwhile, these five aspects will also be used as independent variables of the model. The intensity of outdoor activities of residents in urban settlements is selected as the dependent variable, expressed as the weekly outdoor activity frequency of residents in urban settlements. A total of 300 questionnaires are distributed, 100 per settlement. A total of 284 questionnaires are collected. After removing the blank questionnaires in the retracted questionnaire and the invalid questionnaire with incomplete and regular answers, 269 valid questionnaires were obtained.

4.2. Experimental environment and parameters setting

The basic information of the interviewed residents is demonstrated in Figure 3. There are many projects, so only the one with the most people under each project is selected in the figure.

From Figure 3, of the residents surveyed, 143 are women, accounting for 53.16%. The ratio of men to women is more balanced, with women slightly higher than men. Regarding age, the number of people in the 20–30 age group is the highest. The number of people under 19 and over 61 years old is less, but the age distribution is more widespread overall. Regarding academic

FIGURE 3
Basic information of interviewed residents.

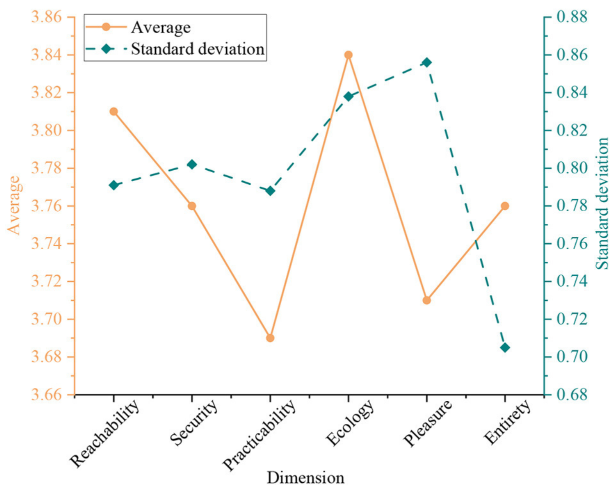

FIGURE 4
Descriptive statistical analysis results of dependent variables.

qualifications, the number of people with bachelor's degrees is the largest, accounting for 61.34%. In outdoor activities, 35.32% of people are active three–four times a week, 42.01% have a single activity time of 1 h, and 68.77% are used to being active at night.

4.3. Performance evaluation

First, the reliability and validity of the questionnaire are tested. Reliability analysis of the data using Statistical Package for the Social Sciences software yields a Cronbach's α coefficient of 0.914 for the comprehensive questionnaire. It is in the high confidence range of $0.7 \leq \alpha \leq 0.98$. The overall confidence of the data of the explanatory scale is high, which meets the statistical analysis standards. The data is tested for validity after reliability testing. After software calculation, the KMO result is 0.94 > 0.6. In addition, the significance of the Bartley spherical test is $p = 0.000 < 0.05$. It shows that the scale data obtained in this study are suitable for factor analysis and meet the data standards.

Second, descriptive statistics are performed on the questionnaire. The descriptive statistical results for the five dependent variables are shown in Figure 4.

From Figure 4, residents rate accessibility, safety, practicality, ecology, and pleasure with an average score of 3.68. Residents rate ecology and accessibility the most, with average scores of 3.84 and 3.81, respectively. Residents rate practicality the least, with an average of 3.69. Residents' overall rating of these five dimensions is 3.76, with a standard deviation (SD) of 0.705. The SD is 0.705. The mean is high, and the SD is small. It indicates that the residents of the three settlements have a good overall evaluation of the public space in the settlements.

Then, a correlation test between variables is performed. The Pearson correlation coefficient test compares the evaluation factors of Q1–Q12 with the outdoor activity frequency of independent residents. Figure 5 reveals the results.

From Figure 5, the p-value of each indicator is <0.01, so it is sorted by correlation. The correlation coefficients of Q11 humanities education fun, Q10 space sunshine ventilation conditions, and Q1 walking distance time are 0.424, 0.416, and 0.398, respectively. They rank in the top three, indicating that these three indicators have the most significant impact on the frequency

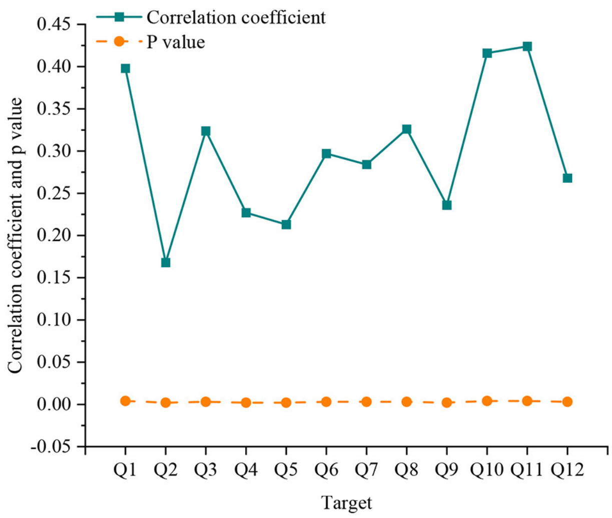

FIGURE 5
Correlation test between evaluation factors and independent variables of each indicator.

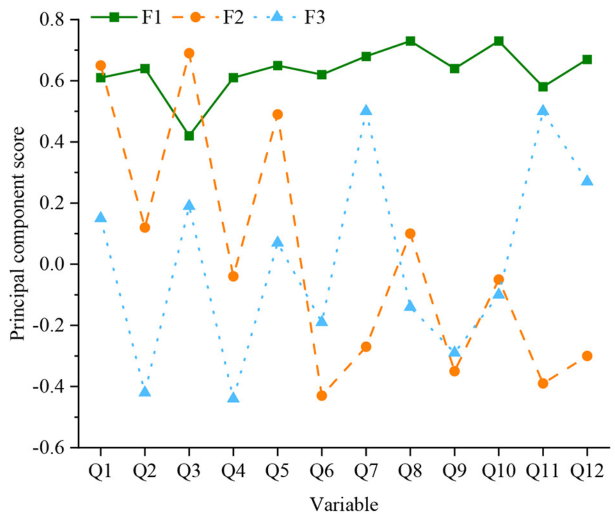

FIGURE 7
Statistics of principal component score coefficient after rotation.

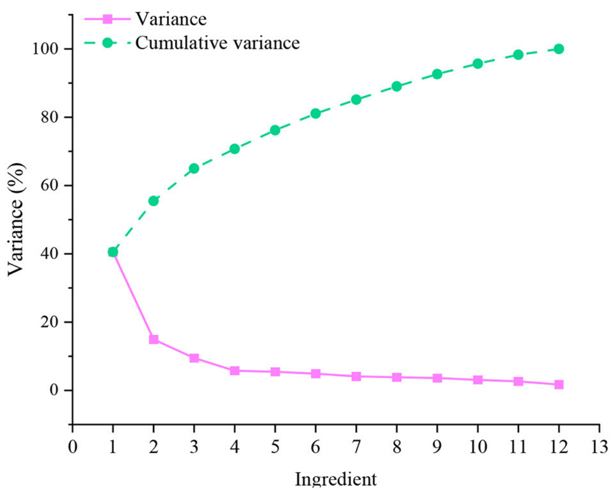

FIGURE 6
Explanatory total variance statistical results.

of residents' outdoor activities. Overall, the *p*-value of the indicator Q1 to Q12 is <0.01. The correlation coefficients are all positive. The results show that all 12 independent variables significantly influence the dependent variable, which meets the statistical test criteria.

Next, MLR analysis is performed on the independent and dependent variables. Explanatory total variance statistics are performed for 12 independent variables. The results are plotted in Figure 6.

From Figure 6, among the total explanatory variances obtained by statistics, the explanatory conflicts of the first three principal factors, with values >1 reaching 64.97%. Therefore, it can be determined that the twelve evaluation indicators can be divided into three dimensions, which the three macro principal factors can explain. There is a strong correlation between the original variables in factor analysis. The factor load matrix can be calculated. So, after the maximum orthogonal rotation of its variance, the factor score coefficient matrix and the rotated load matrix can be obtained. The calculation results are shown in Figure 7.

From Figures 6, 7, the principal factor F1 has a large load coefficient in the six original factors of Q2, Q4, Q6, Q8, Q9, and Q10, exceeding 0.6. The variance contribution rate is 24.07%. The principal factor F2 has a large load coefficient in the three original factors of Q1, Q3, and Q5, exceeding 0.75. The variance contribution rate is 44.72%. The principal factor F3 has a large load coefficient in the three original factors of Q7, Q11, and Q12, exceeding 0.69. The variance contribution rate is 64.97%. Through the understanding of the detailed indicators represented by the three principal factors, they are integrated into the renaming work. F1, F2, and F3 are renamed as public space integrity factor, accessibility factor, and pleasure factor, respectively. The cumulative variance contribution rate of the three is 64.97%, which can explain the composition of the influencing factors of the public space of the settlement on the promotion of residents' health activities. The structural model reintegration is displayed in Figure 8.

After extracting the principal factors, MLR analysis is performed on the three macro factors. The MLR equation is $Y = 0.346F_1 + 0.355F_2 + 0.223F_3 + \sigma$. It can be seen that the accessibility factor F2 of public space has the greatest influence on the outdoor activities of urban residential residents, followed by the integrity factor F1 of public space. The last one is the pleasure factor F3 of public space. Therefore, in the optimal use of public space in settlements, attention should be paid to the integrity and accessibility of public space in urban settlements. Still, the improvement in pleasure should not be ignored.

4.4. Discussion

In summary, the factors affecting residents' satisfaction with the public space of the settlement are mainly the accessibility, integrity,

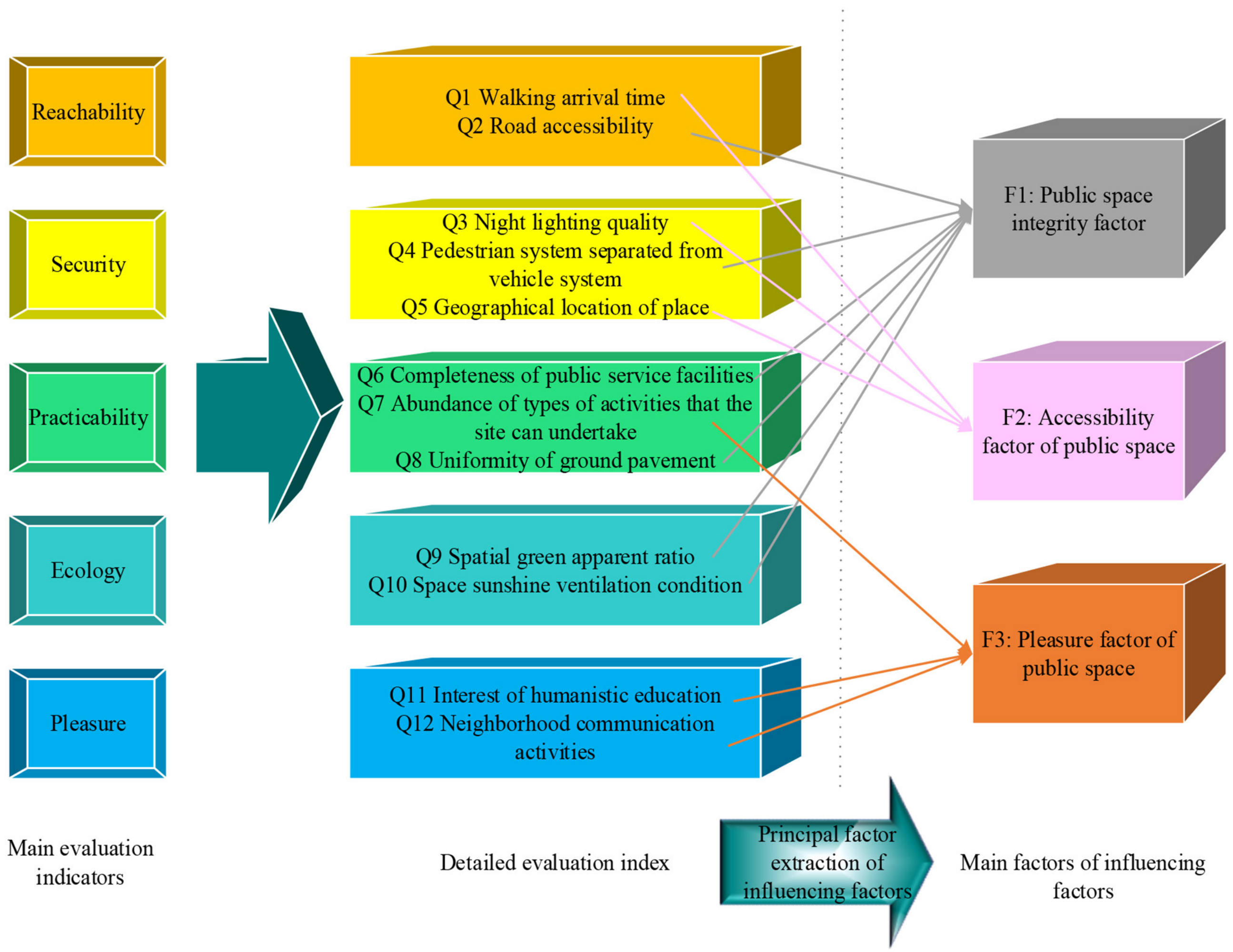

FIGURE 8
Schematic diagram of the extraction of the principal factor of the influencing factors.

and pleasure of the public space. Anastasiou and Manika conducted a field study of residents of a medium-sized Greek city. They surveyed residents on how satisfied they were with urban open space factors. Based on multi-criteria analysis (factor analysis), the factors of residential satisfaction were obtained to capture the shortcomings and dynamic characteristics that shaped urban open space. It was found that residents' satisfaction with urban open space was a function of five factors: the overall operation of open space, the quality of leisure facilities, the contribution of bioclimatic design of large-scale projects, the suitability of infrastructure to children, and respect for local cultural identity (29). Both it and this study confirm that the integrity of public space affects residents' satisfaction with the public space of settlements. Tian et al. chose scenic open spaces in downtown Xi'an, China. The thermal perception (thermal sensation, comfort, and acceptability) of residents and tourists was investigated through meteorological measurements and questionnaires. Physical factors were the main influencing factors of residents' thermal perception, followed by personal, social, and psychological factors (30). Their research angles differ from this paper's, so the results cannot be compared. Jiang and Huang surveyed 7,326 respondents in 78 settlements in Beijing, China. They documented the main characteristics of these residential green spaces and employed multiple logistic regression analyses and multi-level mixed-effects logistic regression analysis. The results showed that having open spaces, gazebos, or shaded paths for numerous activities would significantly increase the likelihood of using residential green area at least once a week (31). The "multi-activity open space, gazebo, or shaded path" is public space accessibility, which is consistent with the findings of this paper. They all show the impact of accessibility in public spaces on satisfaction.

5. Conclusion

This paper studies the connotation and essence of the ecological economy and LCE to explore the influencing factors of residents' satisfaction with public space in settlements. Based on the concept of PH, the characteristics of public space in urban settlements are analyzed. Based on five first-level and 12 second-level indicators, the evaluation model of residents' satisfaction with public space in urban settlements is constructed. The following conclusions are obtained through a questionnaire survey and linear regression analysis: (1) Most interviewed residents engage in outdoor activities at night. There will be three–four activities per week lasting 1 h. (2) The humanities education fun, space sunshine ventilation conditions, and walking distance time have the greatest impact on the frequency of residents' outdoor activities. Overall, all 12 independent variables significantly positively affect the dependent variable. (3) Through the principal factor analysis, the principal factors affecting residents' satisfaction with public space in settlements are the accessibility, integrity, and pleasure of public space, and the degree of influence decreases. In summary, the public space resources of urban settlements can be optimized from accessibility, integrity, and pleasure of public spaces in settlements to promote residents to go to public spaces for outdoor activities and physical exercise, which is more conducive to the PH of residents. However, there are some shortcomings. Only three representative settlements of a city are selected, which cannot cover all cities. It remains to be seen whether the research results can be universalized due to the differences between the North and the South. Follow-up studies can select more samples of cities and settlements for further exploration and summary. In addition, in implementing real-world projects, upgrading public spaces in urban settlements cannot be idealized only for health promotion. Practical projects such as the renewal and renovation of old residential areas and the organic renewal of outdoor spaces in residential areas will include transforming public spaces in urban settlements. Follow-up research can start from this aspect to carry out factor correlation research.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Hunan City University Ethics Committee. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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How do local government information sources affect the purchase willingness of low-carbon agricultural products? The example of regional brand agricultural products

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Introduction: In order to achieve the carbon peaking and carbon neutrality goals, the agricultural sector has been given high priority to reduce carbon emissions. Since consumption is the ultimate goal of production, the consumption of low-carbon agricultural products is of great significance to promote the reduction of agricultural carbon emissions. Regional brand agricultural product is an important tool to promote the development of regional economy to "green, low-carbon, branded and high-quality", and has the technical and institutional conditions to develop into low-carbon agricultural product, so this study takes regional brand agricultural products as the representative of low-carbon agricultural products. As a information source to guide the public to consume in the green and low-carbon way, local government can effectively develop the market for low-carbon agricultural products and drive the development of low-carbon agriculture from the demand side.

Methods: Based on structural equation model with bootstrap method, this paper focuses on the mechanism of the influence of local government information source characteristics (credibility, professionalism, and attractiveness) on consumers' willingness to purchase low-carbon agricultural products, and explores the mediating role of perceived benefits and perceived risks.

Results: The following findings are established: first, the credibility and professionalism of local governments play a positive role in influencing the purchase willingness of low-carbon agricultural products through perceived benefits, with credibility having the greatest degree of influence. Second, the attractiveness of local governments positively influences consumers' willingness to purchase low-carbon agricultural products through perceived risk. Third, perceived benefits play a fully mediating role between credibility and purchase intention, play a partially mediating role between professionalism and purchase willingness, perceived risks play a partially mediating role between attractiveness and purchase willingness.

Discussion: This study provides new ideas for the construction of low-carbon agricultural products and low-carbon development in the agricultural sector from the perspective of local government information sources.

KEYWORDS

low-carbon agriculture, low-carbon agricultural products, regional brand agricultural products, information source characteristics, perceived benefits, perceived risk

1. Introduction

Global warming poses a serious threat to the ecological environment, human health and sustainable economic and social development (1), China committed the "double carbon" target to the international community in September 2020. Human activities are a major source of carbon emissions, with the agricultural sector accounting for 17% of global emissions (2), so the issue of low-carbon emissions reduction in agriculture has received widespread attention. In August 2021, China's Ministry of Agriculture and Rural Affairs issued the "14th Five-Year Plan for National Agricultural Green Development", stating that it would "accelerate the establishment of a green, low-carbon and recycling agricultural industry system". Academics have conducted research on the basic status, potential assessment, and drivers of low-carbon development in agriculture from a production perspective (3, 4), but less attention has been paid to the demand perspective to study the driving role of low-carbon agricultural consumption on low-carbon agricultural development.

Low-carbon agricultural products refer to agricultural products with carbon labels (5), carbon labeling is an important information disclosure tool that can reflect the carbon emissions of agricultural products, and can be used to record the greenhouse gas emissions of agricultural products during the whole life cycle, such as raw material procurement, manufacturing and processing, logistics and transportation, consumption and waste recycling and disposal, etc., and then convert them into carbon dioxide equivalent and inform consumers in the form of labels (6, 7). The establishment of China's carbon labeling system is still in its initial stage, and there are still institutional and technical limitations to the popularization of low-carbon agricultural products. Regional public brand agricultural products (later referred to as regional brand agricultural products) have the potential to develop into low-carbon agricultural products, and it is undoubtedly more efficient to realize low-carbon agricultural development with regional brand agricultural products as the carrier. From the production side, due to the limitations of scale, capital, technology and management ability, it is difficult for new agricultural business entities to independently produce and sell low-carbon agricultural products. In contrast, regional brand built by local governments as the main guide, industry associations, leading enterprises, cooperatives, farmers, scientific research institutions, and other common construction is an important way to promote the regional economy to "green, low-carbon, brand, high-quality" development. Low-carbon agricultural products are the goal of the development of regional brand agricultural products, and regional brand can take the region as a whole unit, gather the power of each stakeholder in the industry, select the type of agricultural products according to the local environment and ecological endowment, and gradually achieve the low-carbon technology application, low-carbon planting, low-carbon processing, low-carbon transportation, and low-carbon sales and other whole process to be low-carbon so as to promote low-carbon agricultural development under the leadership of the local government. From the consumer side, most of the regional brands of agricultural products with characteristics have already gained a certain market popularity after years of development. As a kind of label, regional brand agricultural products can deliver reliable quality signals to consumers, weakening the shortcomings of the diversity of categories and hidden quality of agricultural products themselves. While low-carbon agricultural products, as an emerging label for agricultural products, can deliver reliable quality signals in addition to the concept of green consumption. Relying on the existing regional brands to further develop low-carbon agricultural products, we can not only use the popularity of regional brands to quickly open the market, but also make low-carbon agricultural products more easily accepted by consumers.

Academics have focused on low-carbon agricultural products from the consumer side and discussed them from the perspectives of willingness, attitude, and perception. In addition to the quality of agricultural products, image of origin, and promotional media (8, 9), consumers' willingness to purchase is also influenced by information sources. In this paper, local government is studied as an important information source, on the one hand, it is because the government's information participation plays an important role in enhancing consumer confidence and guiding consumers to establish the concept of green consumption. Due to information asymmetry, consumers in an information disadvantageous position will try to obtain more information from the government, media and other third parties (10), the local government as a reliable information source can transmit signals of reliable quality and guaranteed safety when promoting low-carbon agricultural products, which can effectively solve the problems of information asymmetry and consumers' difficulty in accessing high-quality information. On the other hand, as the main guide and strong engine for the development of low-carbon agricultural products and regional brand agricultural products (11), the local government focuses on the construction of governance system, and the actual information participation behavior is still insufficient. The connection between government and consumers is still loose, the process and effect of information participation are not effectively delivered to the consumer side to enhance the value of low-carbon agricultural products. In addition, studies on government participation in the literature have focused on policy formulation, resource integration, industrial subsidies, and market supervision (12, 13), but there is a lack of research on the impact on consumers' purchase intention from the perspective of information participation, using local governments as information sources.

This paper takes regional brand agricultural products as a representative of low-carbon agricultural products and analyzes the intrinsic mechanism of information source characteristics affecting consumers' willingness to purchase regional brand agricultural products. Perceived benefit-perceived risk is introduced to propose a theoretical framework that the characteristics of local government information sources influence consumers' perceived benefit and perceived risk and thus their willingness to purchase, and finally, the proposed conceptual model and research hypotheses are tested through questionnaire research.

2. Literature review

2.1. Research on the development status of low carbon agricultural products

In order to achieve the goal of carbon peaking and carbon neutrality, the carbon emission detection, reporting and verification system is gaining more and more attention, and the carbon information disclosure mechanism established by carbon labeling has come into being (14), the carbon label for agricultural products is a specific application of carbon labeling in the field of agricultural products, and is an important tool for agricultural carbon information disclosure (15). The carbon label for agricultural products is similar to the existing green label in China, which can provide information on the environment of the origin of agricultural products, supplement the producer's behavior information, carbon emission information, etc., and further improve the quality and price system of agricultural products (14). At present, the carbon labeling system of agricultural products in China is still in the exploration stage (14), and studies have shown that the establishment of carbon labeling system requires high human, material and financial resources, and it is difficult to rely on government power alone to promote it. So, Hu Yu and other scholars believe that it is necessary to accelerate the construction of a sustainable carbon labeling system for agricultural products with the active participation of government, enterprises, collectives and farmers (14). The regional brands of agricultural products are created by local governments, industry associations, agricultural enterprises, cooperatives, farmers, and research institutions (16), which have a good working basis for the development of carbon labeling system.

There are studies prove that regional brand agricultural products can be used as the entry point for the construction of carbon labeling system, Hu Yu and other scholars took Hongze District, Jiangsu Province as an example and introduced the mechanism for the construction of carbon labeling system for rice, the carbon labeling certification system for rice constructed in Hongze District took the regional brand "Forked River Rice" as the entry point, and the mechanism for the construction of carbon labeling system involved the collaboration of local government, rural collective economic organizations, farmers and research institutions. Jin et al. (15) and other scholars summarized the carbon label certification in the field of agricultural production. In the field of primary agricultural products, Tianmu fruit shoots in Lin'an, Zhejiang Province, is the first agricultural product with carbon label in Zhejiang Province (15), which also relies on the establishment of regional brand.

Therefore, with the requirement of low carbon development in agriculture, the importance of regional brand agricultural products in the process of carbon labeling system construction will gradually emerge, and it will become a trend to promote the popularization of carbon labeling with regional brand agricultural products as the main way. So, this paper takes regional brand agricultural products as a representative of low-carbon agricultural products and studies the factors that influence consumers' willingness to purchase low-carbon agricultural products.

2.2. Research on the factors influencing the purchase intention of low carbon agricultural products and regional brand agricultural products

The factors influencing the purchase intention of low-carbon agricultural products and regional brand agricultural products in existing studies can be divided into internal and external aspects. Internal factors are personal and family characteristics of consumers, such as age, education level, income level, cognitive level, etc., (17). Zhang and Guo concluded that the education level of individuals and families has a significant effect on the intention to consume low-carbon agricultural products (18). Wang and Li found that family size has an influence on consumers' purchase of agricultural products (10). Zhao believes that consumers' cognitive level can influence or change consumers' behavior, and the study proved that knowledge level positively influences consumers' willingness to purchase by negatively affecting perceived risk, she also proved that consumption level can positively influence consumers' willingness to purchase by positively affecting perceived benefits (19). Zhang et al. (20) investigated the consumption of vegetables with carbon labels by Shanghai residents, and found that consumers' awareness of carbon labels significantly influenced purchase intentions. Several scholars have explored the consumption intention of low-carbon agricultural products from the perspectives of healthy development (21), environmental attitudes (22), and environmental values (23).

The external factors include the quality of agricultural products, attributes of agricultural products, price, brand image and culture, brand awareness, sales platform, and publicity media. Many scholars believe that the quality and circulation mode of agricultural products affect consumers' consumption intentions by influencing their perceived value and brand trust (24, 25). Yang believes that brand awareness is one of the important factors affecting the consumption of regional brand agricultural products (26). Wang and Wang divided the regional brand image of agricultural products into three dimensions: regional product or service image, user image, and regional industry image, and constructed a model of regional brand image of agricultural products and consumers' purchase intention (27). They proved that each image dimension of regional brand has positive influence on consumers' purchase intention (27). Lai divided brand stories into weak stories and strong stories, and proved that both have positive influence on consumers' purchase intention, and weak stories have better effect (28).

With the popularity of e-commerce live marketing mode, Zhao (29) explored the influence on consumers' purchase of regional brand agricultural products from the perspective of host characteristics. She concluded that the professional, well-known, interactive and emotional nature of hosts significantly influence the formation of consumer preferences and consumption intentions (29). Using e-commerce anchors as an information source, Zhao (29) investigated the effect of their characteristics on consumers' purchase intention. In addition, studies on the characteristics of information sources as an influencing factor have also yielded some results in the literature on consumer purchase intention. Liu et al. (30) found that the professionalism and trustworthiness of information sources can increase consumption intention by promoting consumption confidence, and Meng et al. (31) investigated the inner mechanism of information source characteristics affecting consumption intention, and concluded that information source characteristics can positively influence consumption intention by influencing consumers' perception paths of emotional dependence and face perception, and by influencing the rational path of relationship norm perception.

In summary, studies have proved that in the process of realizing low-carbon agricultural development, regional brand agricultural products have become an important entry point, but there is still a lack of research on low-carbon agricultural development driven by the consumer perspective of regional brand agricultural products. The research on the factors influencing consumers' willingness to purchase low-carbon agricultural products is mostly focused on consumers' personal characteristics and attributes of agricultural products, brand characteristics, platform characteristics, etc., but there isn't enough attention paid to the participation behavior of industrial stakeholders, such as local governments, industry associations and cooperatives in the process of building regional brand and developing low-carbon agriculture. Therefore, this paper further expands on the existing theoretical basis: it focuses on the local government, which plays a leading role in the promotion and production of low-carbon agricultural products, regards the local government as the source of information for consumers, and analyzes the influence of the characteristics of local government information sources on consumers' willingness to purchase low-carbon agricultural products.

In this paper, we analyze the underlying mechanisms that influence consumers' willingness to purchase low-carbon agricultural products from the perspective of information source characteristics, focusing on the following questions: Do local government information source characteristics influence consumers' willingness to purchase? In what way and to what extent do the credibility, professionalism and attractiveness of local government play a role in consumers' willingness to purchase? Do consumers' perceived benefits and perceived risks play a role as mediating variables in this process? What is the extent of their influence?

3. Research hypothesis and theoretical framework

3.1. Research hypothesis

3.1.1. Relationship between information source characteristics and perceived benefits, perceived risks

As a kind of information label, if information source is authoritative and credible enough, can effectively reduce information asymmetry (32), consumers in an information disadvantageous position will try to obtain more information from the government, enterprises, media and other third-party institutions to reduce the disadvantage, and consumers can perceive the utility and value of the product from the information label. So reliable information sources can transmit the safe and guaranteed signals of product quality in an invisible way. There is a significant positive impact on the perceived benefits (10).

Information sources can influence individuals' understanding and perception of product information in terms of three characteristics: credibility, professionalism and attractiveness (31). Credibility refers to the degree of trusting the information source from consumers (33), Endogan believes that the credibility of information sources affects consumers' perceptions of products, and that higher credibility leads to more positive evaluation of products (34) and easier reliance on product brands, Qi and Yang believe that consumers will also give priority to products introduced by their trusted information sources when they have new needs (35). Therefore, when purchasing regional brand agricultural products, consumers believe that the higher the credibility of the local government, the easier it is to make a positive evaluation on the publicity, promotion and products provided by the local government, which can effectively reduce the perceived risks of consumers and enable them to obtain higher expected value in the process of purchase and consumption, thus consumers will have higher perceived benefits. Accordingly, this study proposes the following hypotheses.

H1: The credibility of local government positively affects consumers' perceived benefits.

H2: The credibility of local government negatively affects consumers' perceived risk.

Professionalism refers to the knowledge, experience or skills possessed by the information source that can be referred to (36). Biswas argued that the professionalism of the information source can significantly influence users' risk perceptions and attitudes (37), and that consumers tend to recognize and trust a product when it is promoted by someone with professional knowledge and background (35). Therefore, when consumers buy regional brand agricultural products, the stronger the professionalism of local government, the more adequate its knowledge about agricultural production and cultivation, regional brand construction and operation, the more experienced it is in identifying the authenticity of regional brands, the more qualified it is to promote and publicize regional brands, the higher quality and more persuasive the information output will be. The more effective it will be in enhancing consumers' acceptance, saving the time and energy of information audiences. In other words, professional information sources can reduce consumers' perception of risk and increase their perceived benefits. Accordingly, this study proposes the following hypotheses.

H3:The professionalism of local government positively affects consumers' perceived benefits.

H4: The professionalism of local government negatively affects consumers' perceived risk.

Attractiveness refers to the ability of an information source to attract the attention of the information audience (38), and the information source validity model suggests that the attractiveness of an information source includes familiarity, affection and similarity (39). Attractiveness can arouse the curiosity of information audiences and enhance consumers' attention to information content, and consumers' affection and familiarity with the information source will bring strong perceived value (35). Therefore, when the local government is promoting the regional brand agricultural products, it can follow the development of the times to grab the attention of consumers through new communication methods such as graphic, video and live broadcast, etc. The degree of consumers' affection and familiarity with the local government will be also deepened, in other words attractiveness of local government can increase consumers' perceived benefits. Accordingly, this study proposes the following hypothesis.

H5: The attractiveness of local government positively affects consumers' perceived benefits.

H6: The attractiveness of local government negatively affects consumers' perceived risk.

3.1.2. The relationship between perceived benefits, perceived risks and purchase willingness

In the framework of Perceived benefit—Perceived risk, the higher the perceived benefit and the lower the perceived risk, the more it can positively influence consumers' decisions (40). Regional brand as a quality signal can influence consumers' quality perception of agricultural products and stimulate consumers' associations, such as economic support for local producers (41), and consumers will have higher perceived benefits; and the long-term popularity of regional brand can make consumers have lower perception of risk for after-sales service and other aspects, so consumers' willingness to purchase is stronger. Accordingly, this study proposes the following hypotheses.

H7: Perceived benefits positively affect consumers' willingness to purchase regional brand agricultural products.

H8: Perceived risk negatively affects consumers' willingness to purchase regional brand agricultural products.

3.2. Theoretical framework

Based on the above literature theories and research hypotheses, this paper introduces the perceived benefit-perceived risk framework as a mediating variable to construct the mechanism and path of local government information source characteristics affecting willingness to purchase regional brand agricultural products, and the complete theoretical model framework is shown in Figure 1.

4. Data and methodology

4.1. Data source and variable measurement

4.1.1. Sample selection and data collection

In this study, a random sample of consumers across the country was surveyed using a combination of the Credamo platform and the Questionnaire Star platform. The group issued a total of 356 questionnaires, of which 342 were valid, with an efficiency rate of 96%. From the results of the questionnaire survey, it can be seen that the respondents are mostly female, accounting for 58.5%, the respondents are mostly young, with consumers aged 21–40 accounting for 92.4%, the acquired education is mostly undergraduate, accounting for 70%, most of them are employees of enterprises and institutions, accounting for 75.2%, and the monthly income level is distributed more evenly, the basic situation of the sample is shown in Table 1.

4.1.2. Variable measurement

Characteristics of local government information sources: This study classifies the characteristics of local government information sources into credibility, professionalism and attractiveness. Based on the theoretical study and empirical scale of information source characteristics (31), three characteristics are measured as follows: the questions for credibility include "the information source has good credibility, the released information is reliable, the released information is objective, the released information is complete". The questions for professionalism include "local government has professional knowledge of regional brand agricultural products, has the ability to identify the authenticity of regional brand agricultural products, is qualified to promote regional brand, and is an effective information channel". The questions for attractiveness include "the released information is attractive; the released information gives people a sense of pleasure; the released information is interesting to me; I like the released information".

Perceived risk and perceived benefit: Drawing on the scale of perceived value, this study combines the characteristics of regional brand agricultural products, and measures the perceived risk and perceived benefit as follows: The questions for perceived benefit include "regional brand agricultural products have better quality, the brand is easier to remember, the brand has higher social recognition, the brand can promote low carbon development in agriculture". The questions for perceived risks include "when buying regional brand agricultural products, we worry about buying fake products, we worry about bad taste and flavor, we worry about quality and safety problems, we worry about serious transportation loss, we worry about bad after-sale service".

Willingness to purchase regional brand agricultural products: In this study, the willingness to consume is used as the explanatory variable. In contrast to the explanatory

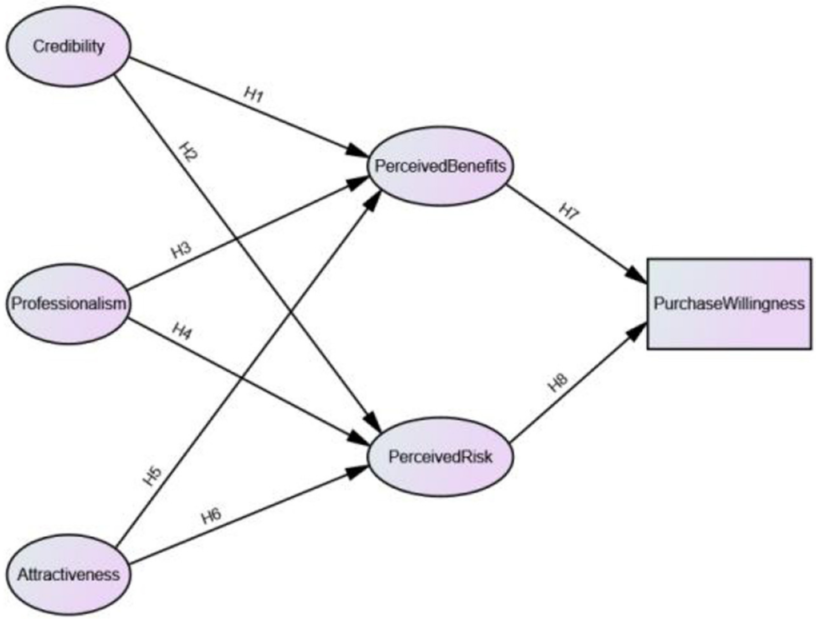

FIGURE 1
The path model of local government information source characteristics influencing the consumption willingness of regional brand agricultural products.

TABLE 1 Respondents' basic characteristics.

Projects	Category	Number	Proportion	Projects	Category	Number	Proportion
Gender	Male	142	41.5%	Age	Under 20	6	1.8%
	Female	200	58.5%		21–30	197	57.6%
Educational background	Junior high school	13	3.8%		31–40	119	34.8%
	Junior college	35	10.2%		41–50	11	3.2%
	Undergraduate	240	70.2%		51 or above	9	2.6%
	Master and above	54	15.8%	Monthly income (RMB)	Under 3,000	69	20.2%
Career	Students	75	21.9%		3,000–5,000	62	18.1%
	State-owned enterprises/ institutions/ civil servants	93	27.2%		5,000–8,000	76	22.2%
	Private/ foreign enterprise	164	48.0%		8,000–15,000	82	24.0%
	Freelance	10	2.9%		15,000 or more	53	15.5%

variables, the credibility, professionalism and attractiveness of local governments need to be reflected from multiple aspects in order to be more scientific, and in contrast to psychological variables that cannot be measured directly, such as attitudes and perceptions, the explanatory variables in this paper refer to existing studies to reflect the purchase intentions of consumers directly through a five-point Likert scale. The question is "How willing are you to buy regional brand agricultural products", which is divided into 5 levels: "very unwilling, less willing, generally willing, more willing and very willing".

4.2. Reliability and validity of the scale

The measurement items selected for this study were all based on the domestic and international literature, and the questions were designed according to the need to study the consumption willingness of regional brand agricultural products, combined with the judgment of experts in the field, so that the scale has surface validity. The questionnaire was pre-researched in two rounds and fully revised for mass distribution. Table 2 shows the results of the statistical tests of the scale reliability and validity, the scale consistency reliability test is based on the Cronbach's α coefficient, and it can be seen from the table that the Cronbach's α coefficient of each concept in this study is greater than 0.8, which is greater than the critical level of 0.7. The scale validity is used to analyze whether the index items are reasonable and meaningful. In this study, the KMO values initially reflected the validity level of the scale, and the table shows that the KMO of each latent variable was between 0.7 and 0.9, which indicates that each measure is suitable for information extraction and has good validity. The standardized factor loadings of measurements on each concept are greater than 0.6, which is greater than the minimum critical level of 0.60 required by relevant studies, indicating that the questionnaire has good convergent validity. The Average Variance Extracted (AVE) and Composite Reliability (CR) of latent variables are used for convergent validity analysis, and the convergent validity is better when AVE is greater than 0.5, and the AVE of each latent variable in this study is higher than 0.5; CR indicates the combination of the reliability of all observed variables of latent variables, and above 0.7 indicates better combined reliability, and the table shows that the CR of each latent variable in this paper is greater than 0.80, which indicates that the consistency among the observed variables of the latent variables is good.

The recovered data were tested for discriminant validity, and the diagonal lines in the table are the AVE square root values, and the remaining values are the Pearson correlation coefficients. If the square root of each AVE in the model is greater than the correlation coefficient between the concept and the other concepts, then this questionnaire is said to have good discriminant validity (42). From Table 3, the square root of the AVE values on the diagonal of each factor is greater than the maximum value of the absolute value of the correlation coefficient between the factors, indicating that the concepts in this paper have good discriminant validity.

5. Empirical analysis

5.1. Model evaluation

In this study, a structural equation model was constructed using the software AMOS28.0. The model fitted the path of local government information source characteristics influencing the purchase willingness of regional brand agricultural products and was modified on the basis of the initial model, and the test results are shown in Table 4. The absolute fit measures, incremental fit measurement and parsimonious fit measurement all meet the requirements, indicating that the research model has good explanatory power and can be used to test the theoretical hypotheses in the previous section.

5.2. Hypothesis testing results

As can be seen from Table 5, the standardized estimated coefficients of credibility and professionalism on perceived benefits are 0.312 and 0.295, which are significant at the 1% level, indicating that hypotheses H1 and H3 are valid, and the degree of influence of credibility on perceived benefits is higher than that of professionalism. On the one hand, this may be due to the fact that the credibility of the local government comes from its long-accumulated reputation and consumers are willing to trust the official endorsement of the local government for regional branded agricultural products due to inertia psychology. On the other hand, local governments play an important role in the whole life cycle of the construction of regional brand of agricultural products. For example, they play the role of advocate and planner in the early stage of construction. After the brand is built, the local governments will be transformed into the supervisor of brand development and the provider of public services, and play the role of support and manager for the subjects involved in brand construction. In the context of the overall leadership of local governments, compared with ordinary agricultural products, consumers are more inclined to trust the quality of regional brand agricultural products, so as to have a higher perception of benefits. Professionalism also has a significant positive impact on consumers' perceived benefits, because the more information released by local governments can demonstrate the expertise in regional brands, such as setting production standards for regional brand agricultural products, providing standards for authenticating brands and providing authentic brand logos, the more consumers can feel the signal of brand quality assurance, and consumers will be more inclined to trust that regional brand agricultural products has higher product quality, thus the consumers' perceived benefits will be increased.

The standardized estimated coefficient of local government attractiveness on perceived risk is −0.353 and is significant at the 0.1% level, indicating that hypothesis H6 is valid, the effects of credibility and professionalism on perceived risk do not pass the significance test, indicating that hypotheses H2 and H4 are not valid. The source validity model considers familiarity, affection and similarity together as the source attractiveness, with the development of the Internet, the channels of government information release are gradually diversified, and consumers will receive information about regional brand agricultural products released by local government through various ways such as graphic, short video and live broadcast, etc. The higher the familiarity and fondness of consumers with local government, the more they will think that regional brands promoted by local governments have lower quality and safety risks, and regional brand agricultural products purchased from official government platforms will have better service guarantees, thus significantly reducing consumers' perceived risks.

As shown in Table 5, the standardized estimated coefficients of perceived benefits and perceived risks on purchase willingness are 0.771 and −0.098, which are significant at 0.1 and 5% levels, indicating that hypotheses H7 and H8 are valid. Because the higher the perceived benefits and the lower the perceived risks, the more consumers can obtain the expected utility in the process of consuming regional brand agricultural products. It can be seen from the comparison of the standardized coefficients that the influence of perceived benefits is greater than the influence of perceived risks. In other words, consumers are more concerned about the actual benefits that regional brand agricultural products can bring in the purchase process, such as higher quality, better taste, and more comprehensive after-sales service of agricultural products.

TABLE 2 Scale reliability, validity, and the confirmatory factor analysis test results.

Concepts (latent variables) and measures (explicit variables)	Cronbach's alpha	KMO	Standardized factor loadings	CR	AVE
Information source credibility (ISC)					
(ISC1) local government has good credibility	0.85	0.82 (0.000)	0.79	0.85	0.59
(ISC2) the released information is reliable			0.75		
(ISC3) the released information is objective			0.74		
(ISC4) the released information is complete			0.79		
Information source professionalism (ISP)					
(ISP1) has professional knowledge of regional brand agricultural products	0.83	0.77 (0.000)	0.79	0.90	0.72
(ISP2) has the ability to identify the authenticity of regional brand agricultural products			0.83		
(ISP3) is qualified to promote regional brands			0.68		
(ISP4) is an effective information channel			0.71		
Information Source Attractiveness (ISA)					
(ISA1) the released information is attractive	0.91	0.85 (0.000)	0.84	0.91	0.57
(ISA2) the released information gives people a sense of pleasure			0.80		
(ISA3) the released information keeps me interested			0.87		
(ISA4) I like the released information			0.87		
Perceived Benefit (PB)					
(PB1) regional brand agricultural products have better quality	0.82	0.83 (0.000)	0.75	0.84	0.50
(PB2) the brand is better packaging			0.60		
(PB3) the brand is easier to remember			0.73		
(PB4) the brand has higher social recognition			0.74		
(PB5) the brand can promote low carbon development in agriculture			0.70		
Perceived Risk (PR)					
(PR1) when buying regional brand agricultural products, we worry about buying fake products	0.89	0.85 (0.000)	0.82	0.90	0.64
(PR2) we worry about bad taste and flavor			0.86		
(PR3) we worry about quality and safety problems			0.90		
(PR4) we worry about serious transportation loss			0.70		
(PR5) we worry about bad after-sale service			0.72		

The brackets of KMO are the size of the *p*-value.

TABLE 3 Discriminant validity: Pearson correlation and AVE square root values.

	Information source credibility	Information source attractiveness	Information source professionalism	Perceived benefits	Perceived risk
Information source credibility	0.77				
Information source attractiveness	0.59	0.85			
Information source professionalism	0.69	0.60	0.75		
Perceived benefits	0.57	0.54	0.59	0.70	
Perceived risk	−0.11	−0.23	−0.08	−0.24	0.80

The results of the model analysis are shown in Figure 2, there is no structural relationship between the credibility, professionalism and attractiveness of local governments, but there is a correlation between them. Table 3 shows that there is a correlation between them and there is good discriminant validity, so the model construction is reasonable. The regression paths that passed the

TABLE 4 Modified model fitness test values.

Projects	Indicators	Threshold	Models	References
Absolute fit measurement	χ^2/df	<3	1.84	Hair et al. (43)
	GFI	>0.8	0.88	Bagozzi and Yi (44)
	AGFI	>0.8	0.85	Bagozzi and Yi (44)
	RMSEA	<0.08	0.06	Hair et al. (43)
Incremental fit measurement	IFI	>0.9	0.95	Hair et al. (43)
	CFI	>0.9	0.95	Bagozzi and Yi (44)
	NFI	>0.9	0.90	Bagozzi and Yi (44)
Parsimonious fit measurement	PGFI	>0.5	0.70	Bagozzi and Yi (44)
	PNFI	>0.5	0.78	Hair et al. (43)

TABLE 5 Standardized path coefficients and hypothesis testing results.

Paths	Standardized estimated coefficients	S.E.	C.R.	P
Perceived benefits <- credibility	0.312	0.104	2.994	**
Perceived benefits <-professionalism	0.295	0.099	2.968	**
Perceived risk <-attractiveness	−0.353	0.087	−4.047	***
Purchase willingness <- perceived benefits	0.771	0.094	8.222	***
Purchase willingness <- perceived risk	−0.098	0.041	−2.406	**

***represents significant at the 1% level, **represents significant at the 5% level.

significance test are marked in the figure, and the paths that did not pass the significance test have been removed.

5.3. Mediating effect test

In this paper, we used AMOS28.0 software to test the effect of perceived benefit and perceived risk as concurrent mediating variables based on the Bootstrap procedure. In total of 2,000 Bootstrap samples were randomly repeated within the original sample with a 95% confidence interval, and the results are shown in Table 6.

In the effect of credibility on consumption willingness, the confidence interval of the direct effect is (−0.072, 0.393), and the range includes 0, that is, the direct effect is not significant; while the confidence interval range of the indirect effect through both perceived benefit and perceived risk does not include 0, indicating that the indirect effect is significant; therefore, perceived benefit and perceived risk play a fully mediating role between credibility and purchase willingness.

In the effect of professionalism on purchase willingness, the confidence interval of the direct effect is (0.042, 0.430), the range does not include 0, that is, the direct effect is significant; and the confidence interval of the indirect effect through perceived benefit and perceived risk also does not include 0, in other words, the indirect effect is also significant; therefore, perceived benefit and perceived risk play a partially mediating role between professionalism and purchase willingness. The indirect effect of perceived benefits accounted for 56% of the total effect, while the indirect effect of perceived risks accounted for 4% of the total effect. Similarly, perceived benefit and perceived risk play a partially mediating role between attractiveness and purchase willingness. The indirect effect of perceived benefits accounted for 46% of the total effect and the indirect effect of perceived risks accounted for 6% of the total effect.

6. Conclusion and discussion

6.1. Conclusion

Based on the survey data, this paper discusses the purchase intention of low-carbon agricultural products in the context of low-carbon agricultural development by taking regional brand agricultural products as a representative of low-carbon agricultural products, empirically analyzes the influence of local government information source characteristics on consumers' purchase willingness, complements the research on building the regional brand and developing low-carbon agriculture, verifies the mediating role of perceived benefits and perceived risks, and further analyzes the types of mediating role. The empirical results show that: first, the credibility and professionalism of local governments play a positive influence on the purchase willingness of low-carbon agricultural products through perceived benefits, with the greatest influence of credibility. Second, the attractiveness of local governments plays a positive influence on consumers' purchase willingness through perceived risks. Third, perceived benefits play a fully mediating role between credibility and purchase willingness, and a partially mediating role between professionalism and purchase willingness; perceived risks play a partially mediating role between attractiveness and purchase willingness.

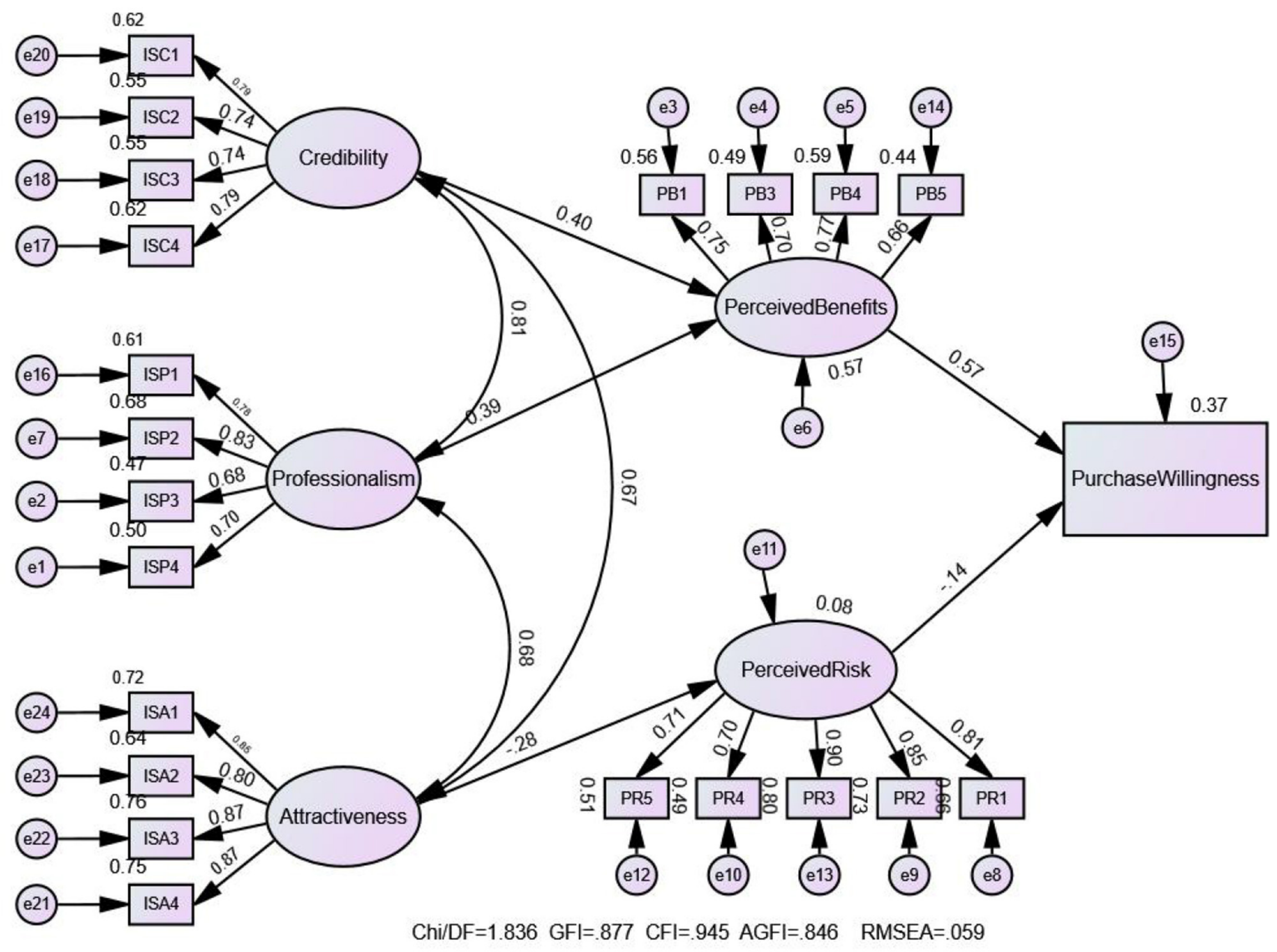

FIGURE 2
Structural equation model analysis results.

6.2. Managerial implications

Based on the above conclusions, in order to promote low-carbon emission reduction in agriculture and develop low-carbon agricultural products with regional brand agricultural products as an important way, local governments as an important source of information need to pay attention to the following aspects.

First, we need to enhance the credibility of local governments and improve the credibility of official endorsements through multiple channels. The credibility of the government needs to be guaranteed by correct leadership and efficient implementation. Local governments, as an important window for uploading and transmitting, should take advantage of the regional brands of agricultural products with good development to actively apply and promote the carbon label for agricultural products by way of pilot projects on the basis of establishing a sound carbon labeling system by the central government departments. The local government's support and supervision of low-carbon agricultural products should be fully implemented. With the local Agriculture and Rural Affairs Bureau as the leading unit, multiple government departments should be cooperated in the process of promoting the transformation of regional brand agricultural products to low-carbon agricultural products. Actively take actions to popularize low-carbon production and planting technology, accelerate the improvement of the carbon labeling system for agricultural products, supervise the quality of low-carbon agricultural products, crack down on fake and shoddy behaviors, and deliver the implementation effect to the consumers through multiple channels, establish a credible image in the minds of consumers, so as to improve consumers' perception of the value of low-carbon agricultural products and agricultural low-carbon development.

Second, we need to enhance the professionalism of local governments and improve the quality of information delivered. As one of the main leaders in the consumption of low-carbon agricultural products, it is crucial for the information delivered by local governments to the public. It is necessary to properly strengthen the professionalism of the information content, focusing on the carbon emission standards, quality identification, quality control and other aspects of low-carbon agricultural products, so as to improve consumers' perception of the quality of low-carbon agricultural products.

TABLE 6 Bootstrap estimation results of mediating effects.

Paths	Effect value	Standard error (SE)	Bias-corrected 95% confidence interval
Direct effect			
Credibility–>purchase willingness	0.134	0.119	(−0.072, 0.393)
Indirect effects			
Credibility –> perceived benefits –> purchase willingness	0.340	0.100	(0.209, 0.638)
Credibility –> Perceived risk –> purchase willingness	0.023	0.015	(0.002, 0.068)
Direct effect			
Professionalism–>purchase willingness	0.247	0.096	(0.042, 0.430)
Indirect effects			
Professionalism–>perceived benefits–>purchase willingness	0.354	0.116	(0.180, 0.665)
Professionalism–>perceived risk–>purchase willingness	0.026	0.017	(0.002, 0.074)
Direct effect			
Attractiveness–>purchase willingness	0.217	0.066	(0.070, 0.341)
Indirect effects			
Attractiveness–>perceived benefits –> purchase willingness	0.209	0.053	(0.141, 0.315)
Attractiveness –> perceived risk –> purchase willingness	0.028	0.017	(0.004, 0.060)

Third, we need to enhance the attractiveness of local governments and create an approachable government image. The plates related to low-carbon agriculture in the official platform can be sorted out and integrated into relevant topics according to the consumers' attention. The information about greenhouse gas emissions of the whole life cycle of agricultural products can be made more visible, readable, and perceptible by means of graphics, short videos, and live broadcasts. The frequency of information release can be effectively controlled in order to increase the consumers' acceptance of local government through high-quality information, so as to enhance the efficiency of the information released by the government to reach consumers.

Fourth, we need to enhance the perceived value of consumers by uniting multiple entities. In addition to local governments, agricultural industry associations, leading enterprises and cooperatives are all important subjects for the promotion of low-carbon agricultural products. The government should unite various forces to upgrade regional brand agricultural products to low-carbon agricultural products, and constantly enhance consumers' recognition of the quality and value of low-carbon agricultural products through diversified and multi-channel publicity methods. The media is also an important player. Local governments should guide the media to help promote and publicize the development of carbon labeling of agricultural products, and convey the concept of low-carbon agriculture and green consumption to the whole society. The basic rights of consumers should be protected to reduce risks in the purchase process, so as to support the development of low-carbon agriculture from the consumer side.

6.3. Theoretical contributions and research limitations

There is a marginal contribution in this paper in terms of research perspective. This paper takes the local government, which plays an important role in the development of low-carbon agricultural products, as the information source, focuses on the important role of local government in the promotion of low-carbon agricultural products, analyzes the influence of local government information sources on consumers' purchase willingness, provides diversified thinking paths for the development of low-carbon agricultural products, and expands the research on the consumer side of low-carbon agriculture.

There are a few shortcomings in this paper. For example, at present, the practice and research of low-carbon agricultural products in China are in the initial time. This paper only discusses the potential and possibility of developing regional brand agricultural products into low-carbon agricultural products from the literature level, but does not build indicators to quantify the potential from the perspective of empirical analysis, and does not show the contribution degree of regional brand agricultural products to the development of low-carbon agriculture through data.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conception and design of study and drafting the manuscript: PX and LW. Acquisition of data: LW, PX, ML, and YL. Analysis of data: LW. Revising the manuscript critically for important intellectual content: PX, ML, and YL. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impacts of health expenditures and environmental degradation on health status—Disability-adjusted life years and infant mortality

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Introduction: Human health and well-being are intimately related to environmental quality. In this respect, the present study contributes to the existing health economic literature by examining whether public and private health expenditures (PPHE) moderate the incidences of environmental degradation on the health status in Saudi Arabia, particularly disability-adjusted life years (DALYs) and infant mortality.

Methods: Using the fully modified ordinary least squares (FMOLS) method.

Results and Discussion: The empirical results revealed that (i) unconditional positive impacts of CO_2 emissions on increasing DALYs and infant mortality; (ii) conditional negative impacts of public health expenditures on DALYs and infant mortality in all the estimated models, whereas global and private expenditure contribute only on reducing infant mortality; (iii) public health expenditure is more effective than private health expenditure in reducing infant mortality; (iv) the effects of the interactions between the indicators of both health expenditures and CO_2 emissions on DALYs and infant mortality are negative and significant only for the specifications relating to public health expenditures, indicating that this later could be employed as a policy or conditional variable that moderates the adverse impacts of carbon emissions on the population's health status. Generally, the study presents an overview of environmental health change's effects and examine how these effects may be reduced through increasing health spending. The study provides recommendations for addressing health status, health expenditures, and carbon emissions, all of which are directly or indirectly linked to the study.

KEYWORDS

health status, mortality, environmental sustainability, carbon dioxide, sustainability

1. Introduction

As a fundamental universal right, health is moreover a major resource for social and economic progress. The World Health Organization (WHO) revealed that all peoples of the world have the right to the greatest attainable typical of health. Health is not only the nonexistence of malady or disability, but also mental, physical, and social welfare. The health sector is the first basic social sector for all countries. An unhealthy environment poses health risks and then a violation of the right to health. In this context, Gwangndi et al. (1) argue that environmental quality directly influences human well-being and health status, whether in urban cities or in the hinterland and it has been established that environmental degradation due to human activities could lead to malnutrition and mortality, morbidity, and shortened life expectancy. It not only hinders health status but also increases health expenditures (2). The present work extends this debate by investigating the effectiveness of health expenditures in modulating the incidences of carbon emissions on the population's health status in Saudi Arabia.

Saudi Arabia pays particular attention to the health sector to enhance the health situations of citizens and residents in general and to protect disabled persons in particular. This is in line with the country's 2030 vision, aimed at guaranteeing a healthy life, supporting the well-being of everyone at all ages and making cities, and ensuring that cities and human settlements are inclusive, secure, durable, and sustainable. However, the rapid urbanization, industrial, commercial, and agricultural evolution of the country has worsened the environment (3). In terms of CO2 emissions, the country is ranked among the top worldwide emitters since its economic activities still depend on traditional energy use and production, causing therefore negative impacts on health status. Moreover, the rapid expansion of oil refineries, land transport, manufacturing companies, and use of pesticides, among others, could increase food, water, and air pollution, which may be, in turn, the invisible cause of certain serious illnesses, such as cancer, birth defects, and other potential hazards to public health (4).

In light of the above motivations and arguments, our study offers several theoretical and empirical contributions to the existing studies. First, from a theoretical viewpoint, health expenditures ensure that public health systems reduce disease risk through a healthy natural environment and promote the green productivity of the economy. They can therefore be an essential factor influencing the quality of the environment. It is therefore substantial to assess the health costs of environmental degradation for the development of both health and environmental policies. Accordingly, the present study seeks to examine the effectiveness of health expenditures in enhancing the population's health status by mitigating environmental degradation. Second, from a methodological viewpoint, despite the growing interest in the environment-health nexus, there is still much to consider in the relationship between environmental degradation and healthcare status, as worldwide anthropogenic emissions due to consumption and production increase in magnitude (5). Unlike prior studies, this inquiry examines for the first time the moderating effect of health expenditures on the environmental degradation-health status (disability-adjusted life years and infant mortality) nexus. Health expenditure has been considered a policy variable that modulates the negative effects of environmental degradation on health status. This later delivers efficient estimates in small sample sizes and makes it possible to deal with the endogeneity problem of the regressors and the problem of autocorrelation. Both aggregated and disaggregated levels of health expenditures are used to examine their influences on reducing environmental degradation for improving health outcomes. To the authors' knowledge, this work is the first to handle such research in this context. It is also the first that analyzes the role of health expenditure in improving environmental quality within the Saudi economy. It, therefore, provides new knowledge to support the establishment of health and green policies in line with the natural environment. Third, in terms of policy viewpoint, our results could be specifically helpful for the Saudi decision-making charging for environmental and healthcare issues and provide some degree of imperative comprehension to other countries with health expenditures and development levels comparable to the Saudi economy.

The rest of the study will go as such. Section two presents the literature review on the relationship among health expenditure, environmental degradation, and healthcare status. Section three explains the data, the econometric model specifications, and the procedures we use to estimate the specified goals. Section four presents and discusses the significant findings and their relevance for policy formulation. Finally, section five contains the study findings and offers some policy implications.

2. Literature review

A large number of papers have recently been interested in exploring the incidences of environmental degradation in human healthcare [e.g., (4, 6–10)]. For instance, the WHO argue that CO2 emissions are the leading causes of environmental pollution and climate change that negatively affect the population's health status in different ways, such as through inhalation, skin contact, and ingestion *via* eye contact. WHO also indicates that over the 2030–2050 period, climate change, caused by increased carbon emissions, is expected to lead to around 250,000 additional deaths per year, according to the same source. In this direction, Zeng et al. (11) examined the contributions of socioeconomic situations, physical environment, and air pollution on the health and survival of seniors in China and they showed that air pollution and low seasonal temperatures augmented the risk of disability, mortality, and health deficits. In the same direction, Owusu and Sarkodie (12) studied the influence of air pollution on disability-adjusted life years (DALYs), mortality, and welfare and they found significant positive and negative impacts of environmental pollution on health status (DALYs, premature deaths, and mortality) and economic development, respectively. Moreover, some recent research has examined the role of health expenditures in developing the population's health status and curbing environmental degradation [e.g., (4, 10, 13–18)]. For instance, Houeninvo (16) examined the consequences of private and public health expenditures on health status for 37 African countries and his results show that public health expenditure effectively improves health status. On the other hand, Ganda (15) examined the role of health expenditure in reducing CO2 emissions for the BRICS countries and he show that both aggregate health expenditures and private health expenditures reduce CO2 emissions, suggesting the need to redesign health spending sub-policies programs to achieve zero carbon goals. The following are the main gaps shared by earlier studies. The first one is linked to the type of relationship among health expenditures, environmental degradation, and the population's health status. Most prior works have examined either the incidences of CO2 emissions on health outcomes [e.g., (4, 9, 10, 19)], effects of health expenditure on health status [e.g., (13, 14, 16–18)], or the nexus between health expenditure and environmental quality [e.g., (15, 20–22)]. However, to the knowledge of the authors, no earlier study has considered these concepts in one study. The second one is the common failure to consider a policy variable that moderates the consequences of CO2 emissions on health status. In this context, we present below the main works dealing with the relationship between environmental degradation and health. In addition, we also review the major works that deal with both the relationship between health expenditures and environmental degradation as well as between health expenditures and health status.

2.1. Environmental degradation and health

There is an abundant literature on the linkage among environmental degradation and healthcare status. It is not possible to make an exhaustive review here, which is why we will present very briefly the most relevant to our research. Starting with multilevel logistic models applied in China, Zeng et al. (11) analyzed the effects of socioeconomic situations, physical environment, and air pollution on health. They found that air pollution and low seasonal temperatures augmented the risk of disability, mortality, and health deficits. By applying the Vector Error Correction Model (VECM) technique, Sinha (23) examined the causal links among industrialization, environmental pollution, and infant mortality rate (IMR) for India over the period 1971–2010 and their findings revealed bidirectional causal links IMR and environmental pollution. In the case of 12 Southern African Development Community (SADC), Mutizwa and Makochekanwa (24) investigated the influence of environmental degradation (CO_2) on IMR with data spanning from 2000 to 2008 by employing static panel estimators (fixed and random effects). The empirical results show that environmental indicators contribute to 38% of mortality. In the same direction, for 66 low-income countries, Chuang et al. (25) explored the interlink between ecological footprints (EFP), environment degradation, IMR, and U5MR during the period 1980–2010 by using linear mixed structures. They found that EFP and environmental degradation does not have any influence on the link among economic features and health status. Furthermore, Fotourehchi (26) examined the impacts of particulate matter 10 (PM 10) and CO_2 emissions on IMR for 60 developing countries for the period 1990–2010 by employing a simultaneous equations model. The findings revealed that the improvements achieved in health outcomes by enhancement of socio-economic situations could be lost by PM-10 and CO_2 emissions. By employing the same method for 30 Chinese provinces, Lu et al. (27) examined the association between carbon emissions, GDP, and public health expenditures during the 2002–2014 period. The empirical results revealed an inverse impact of CO_2 emissions on public health. In an interesting study, Majeed and Ozturk (8) explored the link among CO_2 emissions and IMR in 180 nations from 1990 to 2016 by employing several estimation techniques, such as fixed effects, two-stage least squares, and system-GMM estimators. Their findings revealed that CO_2 emissions generate high IMR. In the same vein, Maiti and Jadhav (28) studied the relationship between three outside pollutants (pollutant minimization program, ozone, and hazardous air pollutants), mortality rate, and DALYs in 164 countries. Empirical findings revealed that the impacts of pollution, deaths, and DALYs rate caused by these outside pollutants are not uniform. Using data for the Middle East and North African (MENA) region, Bouchoucha (29) explored the link among environmental degradation and human health by applying FMOLS and DOLS technologies. The findings show that CO_2 emissions affect inversely health outcomes. More recently, the study of Arafat et al. (30) analyzed the causality relationship between CO_2 emissions, life expectancy, and IMR in the case of Pakistan by applying causality cointegration and causality methods. The causality analysis findings showed the occurrence of a unidirectional link moving from CO_2 emissions to life expectancy and IMR. Similarly, Omri et al. (4) investigated the contribution of research and development in clarifying the link between environmental quality and health status for Saudi Arabia with data spanning from 2000 to 2018 and their results confirmed the negative effect of carbon emissions on health outcomes.

2.2. Role of health expenditures

2.2.1. Health expenditures and environmental degradation

Certainly, the extent of environmental degradation will influence the population's health status, which, in turn, increases health expenditures (4). Several research studies have explored this topic by employing various econometric tools. Most of them have attained the same finding that increasing health expenditures will reduce environmental degradation, particularly CO_2 emissions. For instance, by employing wavelet analysis for Taiwan, Wu et al. (31) investigated the relationship among environmental quality and health expenditures during the 1995Q1-2016Q4 period and they found a causality linkage among the two variables. Before 2004, findings revealed positive causality running from health spending to environmental degradation. However, before 2007, results revealed negative causality moving from health spending to environmental degradation (long-term). For the BRICS economies, Ganda (15) explored the impact of healthcare spending on CO_2 emissions for the period 2000–2017 by using FMOLS, VECM, and Dumitrescu-Hurlin causality techniques. Regarding total and private health spending, the empirical results revealed a negative association with environmental degradation. Nevertheless, public healthcare spending is positively correlated with CO_2 emissions. Besides, causality test results approved bidirectional causality between most of the categorical variables of health spending levels (total, private, and public) and CO_2 emissions. For seven emerging countries, Bu and Ali (22) investigated the effects of health expenditure, GDP, population, and education on CO_2 emissions and they found that health expenditure declines the levels of CO_2 emissions and subsequently improve environmental quality. In the same direction, using the Fourier ARDL (Autoregressive Distributed Lag) model, Li et al. (32) examined the relationships among healthcare spending, environment degradation, and economic growth for the BRICS economies and they found a negative association among environmental degradation and healthcare spending only for India.

2.2.2. Health expenditures and health status

Previous research has made efforts to evaluate and develop the key factors affecting health status and its connection with them. In this subsection, we will review previous studies on the link among healthcare expenditures and populations' health status. Many scholars found that the augmented health expenditures improve health status, such as life expectancy, under-five mortalities (U5MR), infant mortality rate (IMR), disability, and overall death rate [e.g., (13, 14, 16–18, 33)]. However, some other scholars found confusing or unimportant associations among health expenditures and health status [e.g., (34–36)]. For example, Novignon et al. (33) conducted research for the Sub-Saharan Africa (SSA) countries to examine the impacts of private and public health expenditures

(PPHE) on health status between 1995 and 2010. Their findings show that PPHE strongly positively affects health status finished by enhancing life expectancy and reducing IMR. In a similar vein, Karyani et al. (37) compared the influence of PPHE on IMR for Eastern Mediterranean Region (EMR) between 1995 and 2010 by using random effects estimators and they found that public health expenditures reduce IMR; however, private health expenditures do not affect IMR. Furthermore, Nicholas et al. (34) inspected the contribution of PPHE on health outcomes [IMRR, U5MR, and maternal mortality (MMR)] for 40 SSA economies from 2000 to 2010. The empirical findings indicated that public health spending affects negatively and strongly IMR and U5MR, respectively; however, its effect on MMR is negative and insignificant. Raeesi et al. (18) also explored the link among PPHE and three health outcomes indicators (IMR, U5MR, and life expectancy) for 25 countries from 2000 to 2015 and they found a strong link has been observed among PPHE and health outcomes. The contribution of private health expenditure on health status is much higher than public health expenditure. In the same vein, Rezapour et al. (35) studied the impacts of PPHE on IMR, U5MR, and life expectancy as health indicators for selected countries from 2000 to 2015 and their findings revealed that public health spending declines IMR and U5MR, on the one hand; and improve life expectancy, on the other hand. As for private health spending, it has an insignificant effect on the health indicators. For Vietnam, Nguyen et al. (38) explored the associations among disability, health service, and health expenditures. The empirical results indicated that disabled persons had several features of susceptibility (older, less chance of being working, inferior instruction, and poorer) than a person without disabilities. These features have linked with inferior health and advanced need for healthcare use. However, after directing these aspects, disability still had an independent link with advanced health. In the same direction, the main objective of Danovi et al. (39) is to explore the link between lost years due to disability, life expectancy, and health spending in the United States, EU, and several emerging countries in 2017. The findings show that health expenditures have an exponential pace concerning the total of lost years due to disability. Recently, Houeninvo (16) examined the consequence of PPHE on health outcomes (IMR and child mortality) for 37 African countries from 1995 to 2018. System-GMM estimator results show that public health expenditures effectively contribute to reducing mortality. Moreover, Singh et al. (36) investigated the dynamic relationship between PPHE and health outcomes in Southeast Asia by applying the fixed effect, random effect, feasible generalized least squares, and seemingly unrelated regression techniques. Empirical results specified that only public health spending participates in enhancing life expectancy, reducing U5MR levels and mortality rates from non-communicable diseases.

In light of the above-discussed studies, it is clear that most of them have examined either the impact of environmental quality on health status, the impact of health expenditure on health status, or the nexus between health expenditure and environmental degradation. However, slight consideration has been given to the three concepts in one framework. In other words, none of them have examined the effectiveness of health expenditures in reducing the effects of CO_2 emissions on health status (infant mortality and disability-adjusted life years).

3. Methodology and data

3.1. Model specifications

The concern to enhance the population's health status occupies a particularly key place on the scale of priorities of the Saudi community. The present research paper contributes to these debates by investigating the effectiveness of health expenditures in modulating the incidences of CO_2 emissions on the population's health status for Saudi Arabia, particularly disability-adjusted life years and infant mortality.

In addition to the foregoing, the empirical strategy of this leading research is founded on the work of Nelson and Phelps (40) which presents health capital as a crucial element of the absorption and diffusion of technology within an economy thus ensuring a higher growth rate. Implicitly, these macroeconomic models assume that health status is the result of investments in the health sector. There would then exist a production function whose output would be the state of health and for input the resources of the health sector. Following this reasoning, the general form of a health production function can be written:

$$HS = f(H) \tag{1}$$

Where HS represents the health status and H is the health inputs. Following Omri et al. (4), this study split HI into three elements, namely environment (Env), social (Soc), and economic (Eco). So, we obtain the following function:

$$HS = f(Env, Soc, Eco) \tag{2}$$

Since the principal aim of this work is to examine the links among environment, health expenditures, and health status, the economic and social variables are as control variables in the model. Besides, we propose four indicators to measure environmental degradation, specifically *per capita* CO_2 emissions (COpc), CO_2 from liquid fuel consumption (COlfc), CO_2 emissions from electricity and heat production (COehp), and CO_2 intensity (COint). For the social indicators, we included education. For the economic indicators, we included GDP growth. Likewise, the augmented health outcome's function can be presented as such:

$$HS_t = \beta_0 + \beta_1 Env_t + \beta_2 X_t + \varepsilon_t \tag{3}$$

where t designates the time during the period 1990–2020, HS represents the two indicators of health status, Env specifies the four proxies of CO2 emissions, and X represents the control variables, including GDP growth and education, β_0 represents the constant coefficient of the regression and β_1, β_2 refer to the coefficient associated with the four proxies of CO2 emissions and the control variables, respectively.

To explore the effectiveness of health expenditures to modulate the adverse effects of CO2 emissions on health status, Eq. (3) could be written as:

$$HS_t = \beta_0 + \beta_1 Env_t + \beta_2 E\,\mathrm{xp}_t + \beta_3 Env_t * E\,\mathrm{xp}_t + \beta_4 X_t + \varepsilon_t \quad (4)$$

where Exp specifies the three proxies of health expenditure (global, private, and public private). Env*Exp indicates the interactions between the indicators of CO2 emissions and the indicators of health expenditures. β_0 represents the constant coefficient of the specification and $\beta_1, \beta_2, \beta_3, \beta_4$ refer to the coefficient associated with the four proxies of CO2 emissions, the three proxies of health expenditure (global, private, and public private), the interactions between the indicators of CO2 emissions and the indicators of health expenditures and the control variables, respectively. The effect of the interaction between health expenditure and CO_2 emissions on health status has not been studied extensively as we have done so far. The investigation of this type of interaction will generate elements of the answers for us if health expenditure plays a vital role as a moderator in improving the health status affected by CO2 emissions. In this research paper, we use interactions between the three proxies of health expenditure and the four indicators of CO_2 emissions that makes us possible to decide whether there is a complementarity between them in improving health status. We expect that CO2 emissions deteriorate the health status [e.g., (4, 24, 27, 28)], whereas health expenditures improve it [e.g., (13, 16, 35, 37)]. For the interactions between health expenditure and CO2 emissions, we expect that health expenditures modulate the negative effects of CO2 emissions on disability-adjusted life years and infant mortality.

3.2. Estimation procedures

The estimation procedures of our model start by examining the order of integration of series. This step is essential because the employ of non-stationary variables in regression can generate inefficient coefficients, non-optimal predictions, and unacceptable significance tests. Besides, we speak of a time series as stationary when its mean and variance do not vary with time, otherwise, it is said to be non-stationary. In this study, we apply three stationarity tests: Augmented Dickey and Fuller (41), Phillips and Perron (42), and Kwiatkowski et al. (43) tests. Asymptotic distributions of unit root test statistics were constructed assuming the residual term is white noise. Unlike the simple Dickey & Fuller test, the ADF and PP tests consider the possibility of residual autocorrelation in their construction. The first proposes to control autocorrelation directly in the model by including one or more differentiated autoregressive terms. The second, the PP test, proposed a correction of the OLS estimators and associated Student statistics. This is what motivated the choice of these tests.

When deciding the order of integration, the second step consists of identifying the occurrence of cointegrating relationships. The cointegration tests allow noticing that integrated variables of the same order have the same stochastic tendency and therefore a cointegrating relationship. The notion of cointegration can be defined as a long-term systematic co-movement among two or more variables. Granger's and Johansen's tests are well suited for time series. Engle and Granger (44) revealed that it is probable for a linear combination of integrated series of the same order to be stationary with an order of integration strictly lower than that of the variables. The Granger test is based on two steps, the statistical regression between the integrated variables of the same order and the verification of the stationarity of the residuals. Johansen's method consists in imposing restrictions by cointegration and testing them. To test for cointegration and decide the number of cointegrating relationships, the Johansen (45) test has been widely used. It is this test that we apply here as well.

To determine the long-term coefficients, two methods have been proposed (third step). It is known that the Ordinary Least Squares (OLS) technique does not constantly provide stable estimators. In this context, Kao and Chiang (46) suggested the DOLS technique. This last one does not attach immense value to the heterogeneity of individuals. To solve this problem, Pedroni (47) proposes the FMOLS estimator which makes it possible to consider the heterogeneity of individuals, but also the obstacle of endogeneity and autocorrelation. FMOLS estimator not only delivers efficient estimates in small sample sizes but also makes it possible to deal with the endogeneity problem of the regressors and the problem of autocorrelation. FMOLS estimator not only deliver efficient estimates in small sample sizes, but it also makes it possible to deal with the endogeneity problem of the regressors and the problem of autocorrelation. In other words, the FMOLS estimators were developed with the goal of mitigating the effects of endogeneity bias and serial correlation, which would then make it possible to make typical normal inferences. This is accomplished by the FMOLS estimator through the utilization of a non-parametric adjustment.

3.3. Data

The present study uses dataset for Saudi Arabia, spanning from 1990 to 2020, to investigate how health expenditures (global, public, and private) could moderate the impact of CO_2 emissions on health status, particularly infant mortality (IMR) and disability-adjusted life years (DALYs). The period of study was selected given the availability of data for the two main indicators: disability and mortality. We take the logarithm of all used variables. This transformation into logarithm facilitates, on the one hand, the interpretation of the estimated coefficients which are read as elasticities and can control the problem of heteroscedasticity, on the other hand. Indeed, logarithmic transformation makes it possible to resolve or reduce the discrepancies between the variables related to the differences in their units of measurement. Below are the definitions and sources of the variables used (Figure 1).

3.3.1. Dependent variable

The health status' dependent variable is measured by two indicators, namely DALYs and IMR. DALYs, proposed by the World Bank and the World Health Organization in 1993, measures the overall disease burden. One DALY represents "*a one lost year of healthy life and extends the concept of potential years of life lost due to premature death to include equivalent years of healthy life lost by virtue of being in states of poor health or disability*" (WHO). DALYs data were collected from the Global Burden of Disease Study (GBD). IMR is measured by the rates of infant mortality in 1,000 live births. The dataset on IMR is collected from the World Development Indicators (WDI).

3.3.2. Independent variables

As already mentioned, the principal explanatory variables are as follows.

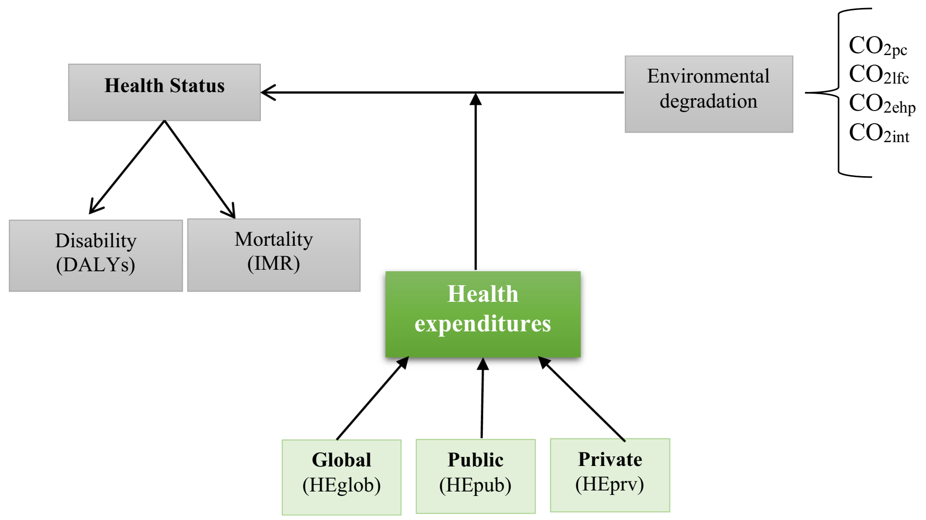

FIGURE 1
The conceptual model of study.

3.3.2.1. Environmental degradation

CO_2 emissions are used as a measure of environmental degradation. Four indicators of CO_2 emissions are considered, namely COpc (metric tons), COint (kg per kg of oil equivalent energy use), COehp (percentage of total fuel combustion), COlfc (percentage of total). Numerous investigations, such as Narayan and Narayan (48), Alimi et al. (49), and Omri et al. (4) have examined the environment-health nexus. Therefore, we assume that CO_2 indicators have positive impacts on the two indicators of health status (DALYs and IMR).

3.3.2.2. Health Expenditures

The effectiveness of public health spending, compared to other health determinants, becoming essential for decision-makers in charge of developing health policies (4). Previous empirical are inconclusive regarding the influence of health expenditure on health status compared to other factors. They revealed that health expenditure often has a positive impact but is mixed in terms of statistical significance (4, 18, 50, 51). The magnitude of the impact of health expenditures depends on the estimation methods and the control variables included in the models. Moreover, the health policy implications of these studies are not easily transposable to the country level, as there are notable socio-economic, demographic, and epidemiological, as well as political differences between countries, especially between developed and developed countries. In this study, we used three measures of health expenditures, namely global, public, and private health expenditures. We expect that global, public, and private health expenditures improve the population's health status in Saudi Arabia.

3.3.3. Control variables

Economic growth and education are included in the model as control variables.

3.3.3.1. Education

Investment in human capital in the form of better health status and higher levels of education is the most effective way to bring about higher productivity (52–55). Education may determine many decisions that influence the quality of life, including choosing a job, being able to choose a healthy diet and avoiding unhealthy habits, using medical care effectively, and so on. This research includes this variable to looking at how education affects health outcomes in Saudi Arabia. We expect that education (Educ) in Saudi Arabia contributes to the improvements of health outcomes.

3.3.3.2. GDP growth

Recent years have been marked by abundant literature on the linkage between many measures of growth and a variety of health indicators (4, 56–58). This study uses GDP growth in annual percentage as a measure of economic growth. We expect that increasing economic growth (EG) improves health status in Saudi Arabia.

4. Results and discussion

The descriptive statistics of the used are presented in Table 1 and Figure 2, which show that, during the study's time period, the value of infant mortality rates range from around 6.6% to around 18.8% per 1,000 live births, whereas the number of healthy years lost ranges from around 5.3 million years to around 8 million years. Bindawas and Vennu (59) argue, in this context, that out of more than 20 million Saudi citizens surveyed, 667,280 of them reported being disabled, representing a prevalence rate of 3,326 out of 100,000 citizens. The values of the indicators of CO_2 emissions range from around 11.7, 47, 58, and 2.3 to around 17.7, 50.4, 89.5, and 2.6 for COpc, COehp, COlfc, and COint, respectively. The values of the two main indicators of health expenditures range from around 62% and 27% to around 73% and 37% of current health expenditure for, respectively, public and private health expenditures. This table also reports a strong correlation between DALYs and IMR (0.928) and between the indicators of CO_2 emissions of up to 0.89. These highest correlations allow us to include them separately in the estimated models to avoid the problem of multicollinearity. The correlations between the two indicators of health status and the indicators of CO_2 emissions are

TABLE 1 Descriptive statistics and pairwise correlations.

	IMR	DALYs	COpc	COehp	COlfc	COint	HEglob	HEpub	HEprv	EG	Educ
Mean	11.720	6506111.1	14.748	48.810	78.269	2.469	4.382	69.515	30.485	3.880	40.961
Standard deviation	3.825	902508.7	2.039	1.153	7.086	0.063	0.971	3.300	3.300	5.431	16.130
Min	6.600	5374414.4	11.724	47.139	57.924	2.367	2.971	61.932	27.018	−3.763	22.321
Max	18.800	8088708.5	17.691	50.486	89.531	2.598	6.262	72.932	37.068	15.193	69.698
IMR	1										
DALYs	−0.928	1									
COpc	0.769	0.729	1								
COehp	0.743	0.683	0.824	1							
COlfc	0.679	0.702	0.856	0.798	1						
COint	0.207	0.251	0.803	0.812	0.891	1					
HEglob	−0.755	−0.798	−0.752	−0.761	−0.571	−0.067	1				
HEpub	−0.588	−0.396	−0.369	−0.399	−0.529	−0.545	0.080	1			
HEprv	−0.588	−0.396	−0.369	0.399	−0.529	−0.545	0.080	0.999	1		
EG	−0.691	−0.740	0.736	0.658	0.617	−0.377	0.449	0.283	0.283	1	
Educ	−0.791	−0.757	−0.318	−0.188	−0.218	−0.157	0.736	0.012	0.614	0.265	1

FIGURE 2
Plots of the main variables.

positive, whereas their correlations with the indicators of health expenditures are negative.

We started our empirical analysis by checking the stationarity of the variables used. Accordingly, different unit root tests are employed, namely ADF (1981), PP (1988), and KPSS (1992). Table 2 reported the results of these tests and showed that all variables are integrated into the first difference, indicating that our variables are integrated in order one (I (1)). Hence, it is possible to check the presence of long-run relationships between the different variables using Johansen's (45) cointegration test. Table 3 reported the results of this test and showed that, at rank = 0, the statistics of the trace test are greater than the critical value, showing the existence of long-run relationships among variables, i.e., the used variables are cointegrated. The next step consists of estimating the long-run relationships using the FMOLS estimator.

Tables 4, 5 present the long-run estimates for IMR and DALYs. It is clear from Table 4 that infant mortality elasticities of the indicators of CO2 emissions are positive and significant in all the estimated models, ranging from 0.098% to 0.215% for the models of the global health expenditure, from 0.122% to 0.177% for the models of the public health expenditures, and from 0.116% to 0.203% for the models of the private health expenditures, meaning that carbon emissions increase infant mortality in Saudi Arabia. This result is in line with Omri et al. (4) who examined the effects of environmental quality and R&D on healthcare status in the same country and found that environmental degradation increases mortality and decreases life expectancy. To moderate the negative effect of environmental degradation on the population's health status, the authors called the Saudi policymakers to support the efforts of R&D and to review and increase their spending on health. In the same direction, Mutizwa and Makochekanwa (24) investigated the influence of environmental degradation (CO2) on IMR for 12 SADC (Southern African Development Community) countries and found that environmental indicators contribute to 38% of infant mortality. However, Chuang et al. (25) explored the interlink between ecological footprints, environmental degradation, IMR, and under-five mortality rate and found that ecological footprints and environmental degradation did not influence the link between economic features and health status. This table also shows that, as expected, health expenditures are negatively correlated with the rates of infant mortality, ranging from −0.302% to −0.412% for the models of the global health expenditure, from −0.492% to −0.602% for the models of the public health expenditure, and from −0.094% to −0.122% for the models of the private health expenditure. The positive contributions of health expenditures on improving the health status confirm the findings of Bokhari et al. (60) who investigated the contribution of health spending and income on health status and found that these variables are necessary factors for improving the population's health status. They argued that an increase in health expenditures would not indeed lead to enhancing the population's health status except these increases were accompanied by institutions, tools, and policies that correctly allocate funds appropriately and characterize intra and intersectoral needs. In the same direction, Similarly, Rahman and Alam (50) also found that private and public health expenditures decrease infant mortality and only private health expenditures reduce the crude death rates. They explain the insignificant impact of public health spending on the crude death rate by the inefficient use of these funds due to corruption and ineffective governance. From these statistics, it is clear that the contribution of public health expenditures (−0.492 to −0.602) is higher than private health expenditures (−0.094 to −0.122), indicating that, in Saudi Arabia, public health expenditures are more efficient than private health expenditure in reducing infant mortality. Therefore, the government may provide enough necessary financial resources to improve the population's health status. This result contradicts the results of Raeesi et al. (18) who explored the link among PPHE and three health outcomes indicators (IMR, U5MR, and life expectancy) for 25 nations and found that the influence of private health expenditure on the health outcomes indicators was bigger than public health expenditure. Moreover, we emphasize one of the gaps existing in the previous research, i.e., examining the efficiency of global, public, and private health expenditures on modulating the negative effects of carbon emissions on infant mortality. Table 4 also shows that the effects of the interactions between health expenditures and carbon emissions on infant mortality are negative only for the specifications related to public health expenditure, ranging from −0.129% to −0.144%. This result indicates that increasing public health expenditures is effective to moderate the negative effects of CO2 emissions on infant mortality. In other words, this research paper concludes that public health expenditures play a significant role as a moderator in enhancing the health status affected by CO2 emissions. This result confirms the findings of Ganda (15), Bu and Ali (22), and Li et al. (32), who found that public health expenditures are effective in reducing emissions, which, in turn, reduces infant mortality (4).

TABLE 2 Results of unit root tests.

Variables	ADF		PP		KPSS	
	Level	1st difference	Level	1st difference	Level	1st difference
IMR	0.711	−5.263*	−1.7992**	−1.634***	0.128*	0.152**
DALYs	−4.119**	−3.938**	−8.470*	−3.954**	0.142*	0.138*
COpc	1.603	−8.520*	1.464	−1.892***	0.150*	0.170*
COehp	−1.556	−3.487***	−1.662	−3.884**	0.113*	0.242*
COlfc	−2.789	−4.884*	−2.300	−7.178*	0.135**	0.167*
COint	−4.022**	−8.015*	−4.031**	−15.176*	0.123*	0.091*
HEglob	−1.385	−3.853**	−1.385	−10.513*	0.177**	0.122**
HEpub	−2.100	−4.619*	−2.081	−4.619*	0.128*	0.068*
HEprv	−2.100	−4.619*	−2.081	−4.619*	0.128*	0.068*
Economic growth	−1.541	−4.109**	−1.541	−4.114**	0.124***	0.121**
Education	−0.286	−6.346*	−0.076	−6.346*	0.240**	0.122**

*, **, and *** indicate the significance level at 1%, 5%, and 10%, respectively.

TABLE 3 Johansen's cointegration test.

Models		Infant mortality rate (IMR)						Disability-adjusted life year (DALYs)					
		Global (HEglob) Model 1		Public (HEpub)Model 2		Private (HEprv)Model 3		Global (HEglob) Model 1		Public (HEpub)Model 2		Private (HEprv)Model 3	
	Rank=0*	Trace test	Critical value (5%)	Trace test	Critical value (5%)	Trace test	Critical value (5%)	Trace test	Critical value (5%)	Trace test	Critical value (5%)	Trace test	Critical value (5%)
COpc	0	203.300	69.818	172.437	69.818	168.679	69.818	164.023	69.818	161.616	69.818	161.197	69.818
COehp	0	173.560	69.818	143.602	69.818	143.437	69.818	140.931	69.818	153.238	69.818	152.002	69.818
COlfc	0	165.185	69.818	148.168	69.818	149.088	69.818	148.830	69.818	169.296	69.818	167.894	69.818
COint	0	157.052	69.818	150.196	69.818	148.720	69.818	143.987	69.818	150.991	69.818	147.383	69.818

* indicates the rejection of the null hypothesis at 5% significance level.

Therefore, policymakers in Saudi Arabia should increase the government spending on health to moderate the influence of carbon emissions on the population's health status, particularly infant mortality. Finally, economic growth and education are found to have positive impacts on reducing infant mortality.

As mentioned above, Table 5 reported the results of the empirical associations among health expenditures, CO_2 emissions, and disability-adjusted life years, showing that DALYs elasticities of the indicators of CO_2 emissions are positive and significant, ranging from 0.083% to 0.197% for the models of the global health expenditure, from 0.109% to 0.184% for the models of the public health expenditures, and from 0.099% to 0.214% for the models of the private health expenditures, meaning that carbon emissions increase the number of healthy years lost in Saudi Arabia, confirming the findings of Owusu and Sarkodie (12) who investigated the contributions of air pollution on DALYs, Mortality, and welfare for 195 countries and they found significant positive and negative impacts of air pollution on health status (DALYs, mortality, and premature deaths) and economic development, respectively. They documented that many high-income countries have recently made efforts to mitigate environmental pollution, which declines DALYs, mortality, and welfare cost. It is reported that environmental degradation, induced by air pollution, contributes to about 103 million DALYs and 4 million global deaths in the year 2015 (61). Table 5 also shows that, as expected, health expenditures are negatively correlated with DALY only for the specifications related to public health expenditure, ranging from −0.226% to −0.368% for the models of the public health expenditures. This result means that the number of years lost due to disability is negatively correlated with the increase of health expenditures, particularly public health expenditures, confirming the findings of Danovi et al. (39) who examined the role of health expenditures in achieving a healthcare sustainability for the United States, the BRICS countries, and the European Union. Their findings revealed a positive association between the number of years lost due to disability and health expenditures. They argued that more resources should be invested not only to diminish the years lost due to disability but also to lower severity, occurrence, and duration of diseases that cause morbidity, comorbidity and polimorbidity, but not mortality. In addition, we focus on another shortcoming in prior studies, i.e., testing the effectiveness of global, public, and private health expenditures on modulating the negative impacts of carbon emissions on the number of years' loss of healthy life (DALYs). Table 5 also reported that the effects of the interaction between health expenditure and carbon emissions on DALYs are negative and statistically significant only for the specifications related to public health expenditures, ranging from −0.118% to −0.188%. This result means that increasing public health expenditures moderate the negative influence of carbon emissions on infant mortality, confirming the findings of Ganda (15), Bu and Ali (22), and Li et al. (32), who found that public health expenditures are effective in reducing emissions, which, in turn, decreases DALYs (12, 61). Therefore, policymakers in Saudi Arabia should increase the government spending on health to moderate the effects of carbon emissions on the number of years' loss of healthy life (DALYs). Finally, most of the control variables do not have the expected signs. Economic growth and education do not have significant impacts on reducing DALYs.

TABLE 4 Results of the impacts of health expenditure and environmental degradation on infant mortality.

Independent variables	Dependent variable: Infant mortality (IMR)											
	Global (HEglob)Model 1				Public (HEpub)Model 2				Private (HEprv)Model 2			
	1	2	3	4	5	6	7	8	9	10	11	12
COpc	0.215**(0.011)	-	-	-	0.177*(0.003)	-	-	-	0.203*(0.000)	-	-	-
COehp	-	0.188*(0.000)	-	-	-	0.169*(0.000)	-	-	-	0.171**(0.019)	-	-
COlfc	-	-	0.098***(0.051)	-	-	-	0.126**(0.038)	-	-	-	0.116***(0.066)	-
COint	-	-	-	0.135**(0.020)	-	-	-	0.122**(0.018)	-	-	-	0.157**(0.040)
HEglob	−0.383*(0.000)	−0.329*(0.000)	−0.412*(0.000)	−0.302*(0.000)	-	-	-	-	-	-	-	-
HEpub	-	-	-	-	−0.535*(0.000)	−0.590*(0.000)	−0.602*(0.000)	−0.492*(0.000)	-	-	-	-
HEprv	-	-	-	-	-	-	-	-	−0.122*(0.000)	−0.109**(0.014)	−0.097**(0.012)	−0.094**(0.036)
COpc * HEglob	−0.061(0.014)	-	-	-	-	-	-	-	-	-	-	-
COehp * HEglob	-	−0.077(0.138)	-	-	-	-	-	-	-	-	-	-
COlfc * HEglob	-	-	−0.058(0.222)	-	-	-	-	-	-	-	-	-
COint * HEglob	-	-	-	−0.087(0.113)	-	-	-	-	-	-	-	-
COpc * HEpub	-	-	-	-	−0.139*(0.002)	-	-	-	-	-	-	-
COehp * HEpub	-	-	-	-	-	−0.154*(0.000)	-	-	-	-	-	-
COlfc * HEpub	-	-	-	-	-	-	−0.129**(0.018)	-	-	-	-	-
COint * HEpub	-	-	-	-	-	-	-	−0.144*(0.000)	-	-	-	-
COpc * HEprv	-	-	-	-	-	-	-	-	−0.086(0.122)	-	-	-
COehp * HEprv	-	-	-	-	-	-	-	-	-	−0.043(0.237)	-	-
COlfc * HEprv	-	-	-	-	-	-	-	-	-	-	−0.011(0.428)	-
COint * HEprv	-	-	-	-	-	-	-	-	-	-	-	−0.082(0.110)
Economic growth	−0.425*(0.000)	−0.289*(0.000)	−0.322*(0.000)	−0.299*(0.000)	−0.440*(0.000)	−0.318*(0.000)	−0.400*(0.000)	−0.302*(0.000)	−0.391*(0.000)	−0.274*(0.000)	−0.336* (0.000)	−0.279*(0.000)
Education	−0.182*(0.000)	−0.152**(0.034)	−0.201*(0.000)	−0.114***(0.052)	−0.177*(0.000)	−0.139(0.112)	−0.198*(0.000)	−0.123(0.133)	−0.211*(0.000)	−0.209*(0.000)	−0.166**(0.028)	−0.184*(0.000)
Constant	9.012*(0.000)	10.328*(0.000)	6.870*(0.000)	3.318*(0.000)	9.523(0.000)	13.244*(0.000)	10.692*(0.000)	8.440*(0.000)	7.254*(0.000)	8.241*(0.000)	9.288*(0.000)	6.052*(0.000)

*, **, and *** indicate the significance levels at 1%, 5%, and 10%, respectively.

TABLE 5 Results of the impacts of health expenditure and environmental degradation on disability.

Independent variables	Disability-adjusted life year (DALYs)											
	Global (HEglob) Model 1				Public (HEpub) Model 2				Private (HEprv) Model 2			
	1	2	3	4	5	6	7	8	9	10	11	12
COpc	0.179*(0.001)	-	-	-	0.162*(0.000)	-	-	-	0.192*(0.000)	-	-	-
COehp	-	0.197*(0.000)	-	-	-	0.184*(0.000)	-	-	-	0.214*(0.000)	-	-
COlfc	-	-	0.083**(0.030)	-	-	-	0.109**(0.027)	-	-	-	0.099***(0.053)	-
COint	-	-	-	0.154*(0.009)	-	-	-	0.183*(0.004)	-	-	-	0.129**(0.019)
HEglob	−0.106(0.110)	−0.049(0.241)	−0.088(0.125)	−0.105(0.147)	-	-	-	-	-	-	-	-
HEpub	-	-	-	-	−0.226*(0.000)	−0.296*(0.000)	−0.368*(0.000)	−0.329*(0.000)	-	-	-	-
HEprv	-	-	-	-	-	-	-	-	−0.113(0.100)	−0.093(0.142)	−0.101(0.114)	−0.084(0.168)
COpc * HEglob	−0.056(0.218)	-	-	-	-	-	-	-	-	-	-	-
COehp * HEglob	-	−0.122(0.107)	-	-	-	-	-	-	-	-	-	-
COlfc * HEglob	-	-	−0.086(0.149)	-	-	-	-	-	-	-	-	-
COint * HEglob	-	-	-	−0.077(0.187)	-	-	-	-	-	-	-	-
COpc * HEpub	-	-	-	-	−0.188*(0.000)	-	-	-	-	-	-	-
COehp * HEpub	-	-	-	-	-	−0.172**(0.015)	-	-	-	-	-	-
COlfc * HEpub	-	-	-	-	-	-	−0.143**(0.010)	-	-	-	-	-
COint * HEpub	-	-	-	-	-	-	-	−0.118**(0.024)	-	-	-	-
COpc * HEprv	-	-	-	-	-	-	-	-	−0.049(0.298)	-	-	-
COehp * HEprv	-	-	-	-	-	-	-	-	-	−0.059(0.325)	-	-
COlfc * HEprv	-	-	-	-	-	-	-	-	-	-	−0.108(0.112)	-
COint * HEprv	-	-	-	-	-	-	-	-	-	-	-	−0.097(0.142)
GE	−0.425*(0.000)	−0.289*(0.000)	−0.322*(0.000)	−0.299*(0.000)	−0.440*(0.000)	−0.318*(0.000)	−0.400*(0.000)	−0.302*(0.000)	−0.391*(0.000)	−0.274*(0.000)	−0.336*(0.000)	−0.279*(0.000)
Educ	−0.182*(0.000)	−0.152**(0.034)	−0.201*(0.000)	−0.114***(0.052)	−0.177*(0.000)	−0.139(0.112)	−0.198*(0.000)	−0.123(0.133)	−0.211*(0.000)	−0.209*(0.000)	−0.166**(0.028)	−0.184*(0.000)
Constant	9.012*(0.000)	10.328*(0.000)	6.870*(0.000)	3.318*(0.000)	9.523(0.000)	13.244*(0.000)	10.692*(0.000)	8.440*(0.000)	7.254*(0.000)	8.241*(0.000)	9.288*(0.000)	6.052*(0.000)

*, **, and *** indicate the significance levels at 1%, 5%, and 10%, respectively.

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5. Conclusion and policy implications

Environmental degradation and climate change and their connections to population health status have recently received much attention. The historical trends of premature deaths, infant mortality, and DALYs costs have a lingering influence on the future development of countries. Accordingly, this study uses dataset for Saudi Arabia to investigate the effectiveness of health expenditures to modulate the negative impacts of CO_2 emissions on health status, particularly disability-adjusted life years and infant mortality. Four indicators of CO_2 emissions (COpc, COehp, COlfc, and COint) and three categories of health expenditures (HEglob, HEpub, and HEprv) are included in the analysis. Necessary econometric procedures, including unit root test, Johansen's cointegration test, and FMOLS method, are used. The empirical results show that (i) unconditional positive effects of CO2 emissions on increasing DALYs and infant mortality; (ii) conditional negative impacts of public health expenditures on DALYs and infant mortality, whereas global and private health expenditure contributes only on reducing infant mortality; (iii) public health expenditures are more effective than private health expenditures to reduce infant mortality; (iv) the effects of the interactions between the indicators of both health expenditures and CO2 emissions on DALYs and infant mortality are negative and significant only for the specifications related to public health expenditure, indicating that this later could be employed as a policy or conditional variable that modulates the adverse effects of environmental degradation on the population's health status. In fact, it has been found that environmental indicators contribute to increase in infant mortality due to environmental degradation. Further, the output of the research paper indicates that increasing public health expenditures is effective to moderate the negative effects of CO2 emissions on infant mortality. In other words, our conclusion is that public health expenditures play a significant role as a moderator in enhancing the health status affected by CO2 emissions. Therefore, policymakers in Saudi Arabia should increase the government spending on health to moderate the influence of carbon emissions on the population's health status, particularly infant mortality.

In light of the above findings, some policy recommendations have been suggested. First, since our findings revealed that public health expenditure could modulate the incidences of environmental degradation on health status, particularly, infant mortality, decision makers in Saudi Arabia are called to review and augment their health expenditures to effectively curbing CO_2 emissions, hence, promoting a healthy environment. Second, CO_2 emissions are found to have negative effects on population health status by generating various bacteria and viruses, which are the causes of different diseases, such as heart problems, bronchitis, and flu-related illnesses like coronavirus (COVID-19) and many other life-threatening conditions. Therefore, urgent measures and appropriate policies toward a low-carbon environment should be taken to foster longevity. Finally, Economic progress allows the population to profit from more developed healthcare facilities; however, the negative externalities of economic activities, particularly environmental pollution, can harm public health. Accordingly, smart, sustainable, and health-friendly economic growth policy reforms will be beneficial in increasing the lifespan of the population. Moreover, it is significant to underline that our work makes interesting contributions to the effectiveness of health expenditures to moderate the adverse effects of carbon emissions on health status, but this does not mask that some other variables like renewable energy, governance, environmental taxation, among others, may be included as moderator variables. Future research could extend this work by considering the roles of the above-mentioned variables.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AO, BK, and MK: software and writing—original draft preparation. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

Table A.1. Data source and expected signs of each variable.

Indicators adopted	Variables	Expression	Sources
Health status indicators	All-cause DALYs (years per 100,000 inhabitants), all ages.	DALYs	GBD (2019)
	Infant mortality as rate per 1,000 live births.	IMR	WDI (2021)
Environmental degradation indicators	Carbon dioxide *per capita* (metric tons)	CO_{pc}	WDI (2021)
	Carbon dioxide intensity (kg per kg of oil equivalent energy use)	CO_{int}	WDI (2021)
	Carbon dioxide emissions from electricity and heat production, total (% of total fuel combustion)	COehp	WDI (2021)
	Carbon dioxide emissions from liquid fuel consumption (% of total).	COlfc	WDI (2021)
Economic and social indicators	Current health expenditures (%of GDP)	HEglob	WDI (2021)
	Public Health Expenditures (domestic general government health expenditure (%) of current health expenditure)	HEpub	WDI (2021)
	Private Health Expenditures (Domestic private health expenditure (%) of current health expenditure)	HEprv	WDI (2021)
Control variables	FDP growth (%)	EG	WDI (2021)
	Gross enrollment rate in tertiary education (%).	Educ	WDI (2021)

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The impacts of low-carbon city pilot policies on natural population growth: empirical evidence from China's prefecture-level cities

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Introduction: The carbon emissions that cities contribute drive the development of low-carbon cities (LCCs) and low-carbon city pilot (LCCP) policies. However, the lack of comprehensive understanding regarding the impacts of LCCP policies on natural population growth hampers effective policy design and implementation, thus constraining sustainable development at the city level.

Methodology: Extending the existing papers which focus on the relations between low-carbon pilot policies and industry transformation or economic growth, this research applies several experimental methods [e.g., Propensity Score Matching-Difference in Differences (PSM-DID)] to investigate the impacts of low-carbon pilot policies on natural population growth by applying the data from 287 prefecture-level cities in China from 2003 to 2019.

Results and Discussion: This research found that low-carbon pilot policies would positively influence the low-carbon cities' natural population growth by influencing (a) economic factors, (b) political factors, (c) technological factors, and (d) the living environment. This research establishes a framework for understanding the impact mechanisms of LCCP on natural population growth. This paper investigates how industrial structure optimization, policy design and implementation in different regions, technological innovations, and urban green space theoretically affect natural population growth. This paper also proposed characteristics of LCCP which should be theoretically concerned by the government. From a practical perspective, this research suggests several policy recommendations. Central and local governments are encouraged to prioritize industrial structure optimization and assess populations' dependence on cultivated land. Providing additional policy support to underdeveloped areas is crucial to promote the balance between economic and environmental development. Furthermore, establishing online public health platforms and urban green spaces is proposed to enhance the population's health and complement the implementation of LCCP policies. This offers both theoretical and practical insights into the impacts of LCCP policies on natural population growth. Its findings contribute to designing and implementing LCCP policies in China and other developing countries at a similar development stage.

KEYWORDS

low-carbon city (LCC), low-carbon city pilot (LCCP) policy, natural population growth, carbon emissions, China

1. Introduction

In 2021, the urban population rate worldwide was 56% (1), highlighting the significance of rapid urbanization on global sustainable development (2). While contributing 70% of the global GDP, cities also produce 70% of global greenhouse gas emissions (3, 4) and have challenged the sustainable development of urban areas and the planet (5). Hence, cities are expected to develop economic, social and environmental conditions (6) to deal with the environmental and climate issues caused by urbanization (7), such as facilitating Low-carbon City (LCC) development (8) by introducing low-carbon city pilot (LCCP) policies (9). Developing low-carbon pilot cities is expected to achieve a win-win between economic growth and environmental protection (9). After all, economic growth should not be achieved by sacrificing the environment (10), which fits into the carbon reduction action plans made by countries worldwide (11).

The emergence of "Low-carbon Cities" (LCCs) is coined in response to the increasing demands for carbon emissions reductions and global warming alleviation (12–14). LCCs refer to a sustainable urbanization approach which connects the government, private sectors and civil societies to reduce cities' carbon footprint by minimizing fossil fuel consumption (15). Since the concept of "low carbon" was first proposed in the UK energy white paper in 2003 (16), the low-carbon transformation in economic development and perceptions on consumption have been undertaken by cities to enhance competitiveness (6). For instance, approximately 60% of C40[1] cities have set carbon reduction targets or developed action plans for climate change (13). To conclude, the policies for LCC development issued and implemented by governments worldwide (11) have highlighted the new directions for cities' sustainable operations (8).

As the largest developing country (17) and carbon emitter of the world (18, 19), China has already set climate targets, such as achieving the "carbon peak" in 2030 and "carbon neutral" in 2060 (17). Based on Huang et al. (20), China's low-carbon development aims to fulfill the transformation from "green low-carbon cities" to "high-quality cities," which shift from low energy consumption/pollution to sustainable human settlements. Low-carbon City Pilot (LCCP) policy is always seen as a macro-level policy (21), which points out the direction for optimization of industrial and energy structure (22). Additionally, LCCP policy is argued to play a crucial role in combining environmental regulation tools at the micro level (23). Since 2017, over six provinces and 81 cities in China have been impacted by the LCCP policy (24), reflecting China cities' initiatives to respond actively to climate change and low-carbon transformations (23).

The relationship between natural population growth and LCCP policies promoting economic and environmental development balance in China is still worth investigating because it determines whether the existing economic development pattern is sustainable (25). However, the existing LCCP-relevant studies mainly focus on policy analysis, design and evaluation to promote low-carbon economic and transport system development (20) rather than further investigate their impacts on natural population growth. After all, the LCCP policies marked by making cities' economic and social development patterns more low-carbon-oriented (26) are not treating natural population growth as their central concern. Unfortunately, natural population growth is found critically influences economic growth [e.g., (27–29)] and the environment [e.g., (30)], although how it works is still under discussion (31). Additionally, based on scholars [e.g., (20)], it is still crucial for China to consider the pathways to optimize the policy mechanisms to facilitate the development of a greener and more liveable city, which can be seen as a new stage for eco-cities development in China. However, the existing studies [e.g., (32–34)] tend to focus on the impacts of LCCP policies on industry transformation and economic growth rather than investigating its impact mechanisms (35) from the LCC level (36). Consequently, the existing studies show limited insights into the relationships between LCCP policies and natural population growth, especially at the city level. Different from the previous studies investigating the impacts of LCCP policies from the industrial transformation or development perspective, this paper is expected to investigate the impacts of China's LCCP policies on LCC's natural population growth. Therefore, this paper is expected to theoretically contribute to (1) building and enriching a framework of LCCP policies' impact mechanisms on natural population growth and (2) emphasizing the factors of LCCP policies the LCCs should consider. This research practically suggests several policy recommendations for policymakers to effectively implement the LCCP policies with a reasonable natural population growth, thereby contributing to LCCs' sustainable development in China and offering successful examples for large carbon emitters worldwide to achieve city-level sustainable development.

This research makes efforts to use empirical methods to answer the question above. We collect data from 287 prefecture-level cities in China from 2003 to 2019. This paper uses LCCP policy as the core explanatory variable, and the natural population growth rate is used as the explanatory variable. Mechanism variables and control variables are also considered. Robustness tests, parallel trend tests, placebo tests, the Propensity Score Matching-Difference in Differences (PSM-DID), bacon decomposition, and modified DID estimation are used. Finally, heterogeneity and mechanism analyses are conducted to conclude that LCCP policies can promote natural population growth by influencing (a) economic factors, (b) political factors, (c) technological factors, and (d) the living environment. This research theoretically contributes to knowledge by building a framework of LCCP's impact mechanisms on natural population growth based on the empirical findings above. Furthermore, this research theoretically enriches several crucial features of LCCP policies which should be considered to optimize the effects of LCCP on rational natural population growth, such as time-lag effects, LCC's administrative level and locations, and supporting policy supplements. From the practical implication perspective, this research recommends that policymakers and enterprises smartly design and implement LCCP policies to contribute to rational natural population growth and achieve sustainable development.

This paper is structured as follows. In the literature review section, this paper starts with the concept of LCC and discusses the impacts of natural population growth on economic growth and the environment. Then, the impacts of LCCP policies on LCC's natural population growth were discussed based on the factors driving natural population growth synthesized from extant studies. The data collection and analysis approaches are explained next. We then report the empirical findings of the statistical analysis, which clarifies the impacts of LCCP policies on natural population growth in the chosen sample LCCs. Last, the

1 C40 Cities Climate Leadership Group (C40) is a network of the world's megacities engaging in reducing greenhouse gas emissions (13).

theoretical implications of this paper are discussed by comparing our findings with previous relevant studies and recommendations for future research are made after explaining the practical guidance brought by this research.

2. Literature review

This section can be divided into four parts. Section 2.1 focuses on the impacts of population growth on economic and environmental development to consolidate the necessity of this research. Section 2.2 synthesizes the driving forces of natural population growth from relevant papers, which was the basis for building links between LCCP policies and natural population growth in section 2.3. The logic of this section is to analyze the relationship between LCCP policies and natural population growth by discussing (1) what drives natural population growth and (2) how LCCP policies would affect the driving forces of natural population growth. After all, as limited studies are engaging in the impact mechanisms of the LCCP policies (35, 37) from the LCC-level perspectives (36), we can hardly build direct relationships between the above keywords. The figure below (see Figure 1) illustrates the logic of conducting the literature review:

2.1. Impacts of population growth on economic growth and environment

The relationship between population growth and economic development has been contentious in economics-relevant studies (31). Some scholars (28, 38–40) argue that population growth facilitates economic growth. For instance, Tiwari (40) and Aiyetan and Olomola (38) empirically found unidirectional causality among population growth, CO2 emissions and economic growth, which means that economic growth occurs accompanied by the increasing population and CO2 emissions. Similarly, Rahman et al. (28) reported that the population and economy grew simultaneously in China and the United States over the last 40 years. For instance, Zhang et al. (41) pointed out that the increasing urban population drives large-scale constructions of infrastructure and buildings in China, facilitating the development of the secondary industry. Furthermore, Bloom et al. (39) mentioned that population growth would positively affect economic growth through knowledge capital accumulation. Similarly, the neoclassical economics paradigm also regarded population growth as the catalyst of technological development and other positive changes (42). Furthermore, Park (43) found that population growth positively influences economic growth when the growth of population and per-capita GDP are independent.

Nevertheless, some papers (27, 29) found that negative population growth would benefit economic growth. For instance, unlike the opinions proposed by Bloom et al. (39) above, Bucci (27) argued that the shrinking population allows individuals to acquire new knowledge easier, enhancing economic growth by facilitating technological progress. Furthermore, population growth requires more cultivated land, driving more countries to issue cultivated land protection policies to support the growing population (44). However, Deng et al. (45) empirically found that the GDP developments of secondary and tertiary industries reduce cultivated land, which means that the population growth contradicts the developments of secondary and tertiary industries in some cases. Additionally, Sasaki and Hoshida (29) empirically found that the economy's capital stock can be distributed to fewer individuals when the population decreases, increasing the per-capita income in the long term. Similarly, Gupta et al. (46) pointed out that the increasing population and child dependency ratios constrain countries' investments in expanding production and reduce per-capita income.

On the other hand, some studies (27, 47) indicated that the correlation between population growth and economic growth is non-linear. Unlike Sasaki and Hoshida (29) and Gupta et al. (46), Christiaans (47) found that the correlation between population growth and economic growth is more complicated since the per-capita income grows only if the negative population growth rate can reach a particular level. Furthermore, the impacts of population growth on economic growth should also be determined by the degree of altruism of individuals toward future generations (27). Additionally, Lin et al. (48) empirically proved that although per-capita GDP positively influences per-capita carbon emissions, the correlation between population growth rate and per-capita GDP is insignificant.

The impacts of population growth on environmental development also link to sustainable development, which refers to "meeting the

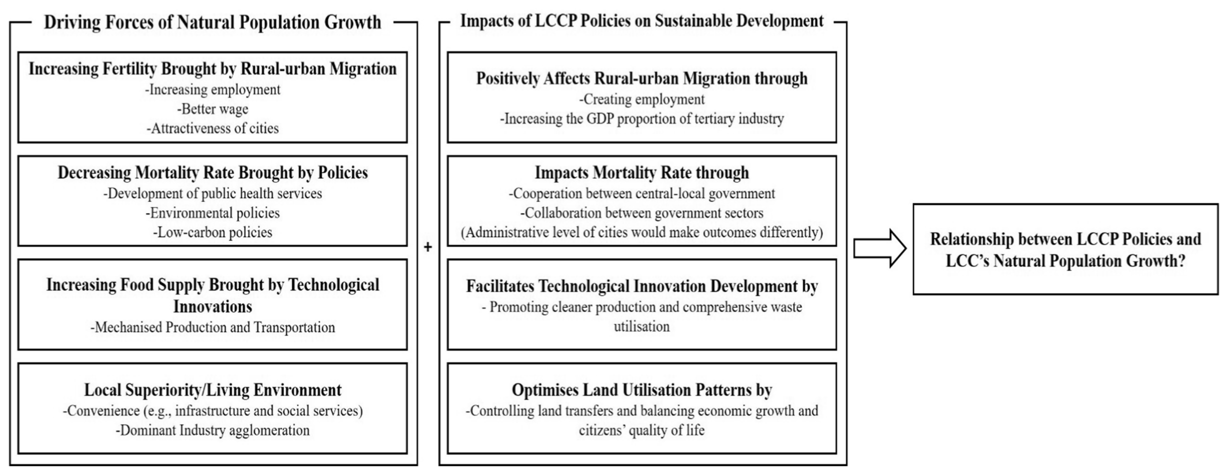

FIGURE 1
The logic of literature review.

needs of contemporary people, but not endangering the development of future generations" (49). World population growth is a crucial factor in environmental degradation, making environmental change adaptation even more difficult (50). To specify, population growth threatens the arable land to produce food and settlement, bringing a mass of energy consumption and industrial wastes (42) and imposing substantial pressure on the environment (30). Wang and Yang (51) get a similar answer from a China-based empirical study as they argue that population growth increases the demand for goods and services and causes increasing pollutants and environmental deterioration (e.g., green areas' decreases or damages). Therefore, decelerating population growth would contribute to sustained development by balancing economic growth and environmental protection. On the other hand, Kabisch and Haase (52) pointed out that offering citizens urban green space (UGS) would be a challenge since the increasing population influences housing development and urban planning.

Furthermore, to expand the UGS-relevant viewpoints above, existing scholarly papers have empirically demonstrated that population growth has an adverse impact on citizens' physical and mental well-being by compromising the availability of UGS. For instance, Kondo et al. (53) revealed that UGS exposure negatively associates with mortality, heart rate and violence. Moreover, Nutsford et al. (54) emphasized that enhanced accessibility to UGS contributes to reducing treatment counts of anxiety/mood disorders, which means that the citizens would be more likely to experience mental issues when the UGS is converted into construction sites. However, the potential health risks of UGS were found by Wolch et al. (55) as they proposed that the UGS near the heavy traffic area may damage public health if interventions focus on encouraging walking and cycling without reducing air pollution.

Population growth contributes to climate change through excessive agricultural activities and fossil fuel consumption (56). For instance, the extreme coastal water levels caused by climate change severely impact the ecosystem of coastal zones and threaten people and infrastructures in these areas (57). Maja and Ayano (30) also pointed out that population growth increases deforestation and degradation, contributing to greenhouse gas emissions and exacerbating global warming. Moreover, human activities influence soil conditions, leading to extensive degradation and exhaustion (58). To sum up, demographic foresight (e.g., recognizing the future trajectories of the world population) matters for a more sustainable future (59).

However, Edeme and God (60) indicated that population reduction policies cannot always solve environmental issues since strong and quality institutions should be utilized as supplements, such as enforcing and implementing environmental laws. Additionally, the population always links to religious and cultural barriers, making population regulation a sensitive topic and difficult to implement (30).

After discussing the possible impacts of natural population growth on economic and environmental development, the next section will focus on the driving forces of natural population growth, which is the basis for building relationships with LCCP policies.

2.2. Driving forces of natural population growth

Natural population growth considers the average annual rates of births and deaths over a long term, which reflects a country's/region's population age structure (e.g., the aging population) (61, 62) and demographic dynamics (63). Since the natural population steadily evaluates the local demographic systems, it is always utilized to measure cities' paths of socioeconomic transitions (64).

Natural population growth is responsible for urbanization, especially in the developing world (65). Based on relevant studies, natural population growth is caused by (1) the increasing fertility brought by the rural–urban migration (65–67), (2) the declining urban mortality rate (65, 68, 69), (3) the increasing urban food supply brought by technological innovations (68), (4) location superiority and decent residential environment (70). This section will outline and discuss the four aforementioned driving forces that influence natural population growth, as it is the foundation for examining the potential influence of LCCP policies on natural population growth via affecting these driving forces.

The rural–urban migration is the result of economic growth. Countries experienced rapid economic growth following World War II (68), which facilitated the growth of the urban labor market [e.g., the increasing urban employment (71) and wage (65, 72)] and made urban areas more attractive (73, 74). Consequently, the migration from rural areas would eventually change into urban-born populations and positively affect the fertility in urban areas, although urbanization cannot be seen as a single process (71). However, the natural population growth brought by migration would be slower because the labor market cannot digest fast-growing populations (67), which causes the re-distribution of population or even counter-urbanization (71). For example, Barreira et al. (66) found that the unemployment rate negatively affects population growth since households intend to find other cities.

Policies influence the decreasing urban mortality rate. Based on scholars (65, 68), the declining urban mortality rate is highly relevant to the development of public health service systems and epidemiological transition. Furthermore, to mitigate the negative effects of environmental pollution on human fertility (75), the environmental policies implemented by countries, such as air pollution prevention and control, reduce infant mortality and contribute to the natural population growth rate (76). Moreover, the low-carbon policies reduce chronic disease incidence and improve human health outcomes (77, 78)—reducing the local mortality rate. Unfortunately, the government's ability to provide basic services would be constrained by rapid population growth, which would eventually reduce citizens' life quality, such as suffering inadequate social resources and networks (67).

The increasing urban food supply is caused by technological innovations, such as mechanized production and the introduction of railways/road transportation (68), which further solve starvation and increase natural population growth. Garenne and Gakusi (79) noted that food riots and declining nutrition led to slower natural population growth in both rural and urban areas in the 1990s in Zambia. However, it is worth mentioning that the conflicts between food supply and urbanization should be further considered. After all, converting from arable land to urbanization land would enlarge the gap between food demand and supply (80) and threaten natural population growth. Moreover, as proposed by Ding (81), population growth would be greater than the food productivity of land and eventually fail to meet the food demand of human beings.

Location superiority/decent living environment is more likely a converging factor since Cai et al. (82) emphasize that the gaps in life quality and living environment between rural and urban areas drive rural people to move to cities, influencing population growth. The convenience and satisfying infrastructure attract potential residents and prevent the existing population from moving out—the location advantages brought by better social services (67), convenient transportation, and dominant industry agglomeration attract more migration (70) and contribute to natural population growth. Nevertheless, the city's development and citizens' quality of life should be balanced. Otherwise, the industries would occupy residential or arable land (70), negatively impacting natural population growth by constraining migration and food supply.

In this section, the four driving forces of natural population growth, namely (1) rural–urban migration, (2) decreasing urban mortality rate driven by policies, (3) more advanced technologies, and (4) location superiority, have been synthesized and discussed. In the next section, we will analyze how the LCCP policies would affect the aforementioned driving forces of natural population growth and further explore how LCCP policies would influence natural population growth.

2.3. Low-carbon city pilot policies and natural population growth

Low-carbon city pilot (LCCP) policy is a crucial low-carbon program of the world since it measures to what extent cities can achieve the goal of carbon prevention and control (83), especially in developing countries. LCCP policy intends to optimize governmental governance by diminishing the trend of sacrificing the environment for economic growth, such as supporting carbon reductions by fiscal expenditure and strengthening carbon emissions constraints on carbon emitters (10), and accumulating experiences for prompting low-carbon cities (LCCs) (11). Unfortunately, the impact mechanism of LCCP is not sufficiently revealed (35, 37). More importantly, when conducting carbon emission-relevant studies, the analysis at the LCCs level is limited (36). Hence, this section will synthesize the impacts of LCCP policies on sustainable development and then combines the findings in section 2.2 to further discuss the possible mechanisms of LCCP policies on natural population growth from the perspective of LCCs.

Zhang et al. (36) empirically found that LCCP policies would drive pilot cities to explore sustainable development patterns, such as developing modern financial industry and cultural and creative bases. Consequently, the pilot countries would achieve a win-win for economic development and environmental protection (9). Specifically, LCCP policies create employment (84) while increasing the GDP proportion of tertiary industry (36). Based on the findings in section 2.2, economic growth (e.g., better per-capita GDP and wages) would speed the rural–urban migration and, therefore, contribute to natural population growth.

However, some existing studies [e.g., (85)] also propose that the LCCP policies would influence the development of LCCs in different regions or at different development stages, thereby theoretically affecting the regional natural population growth differently. For instance, Wang et al. (86) discovered that cities in China with medium or better quality are predominantly concentrated in the Central and Eastern regions, which possess decent incomes and industrial structures, enabling more effective implementation of LCCP policies (87). As a result, the more appealing LCCs above would rapidly expand to saturation (88), thereby contributing to natural population growth. Comparatively, due to the limited fiscal capacity and limited policy leverage (89), the LCCs situated in the Western region are compelled to curtail their economic growth to comply with emissions reduction targets—which exacerbates the existing economic disparity with the Eastern regions (88). Consequently, the natural population growth would be negatively affected since labor forces exhibit reduced enthusiasm for migrating to the Western regions.

Combining the findings mentioned in section 2.2 and the earlier analysis, the different features and outcomes of LCCP policies implemented by LCCs would influence the natural population growth differently. LCCP policies emphasize central-local government cooperation and collaborations between different government sectors. For example, in responding to the central government's action plans on low-carbon development, the local governments would introduce various policies and promote communications and collaborations between government sectors (35). More importantly, the local government at different administrative levels (89, 90) or development stages (91) would apply for different pilot programs, making the focus, goals, and enforcement degree different. As a result, the outcomes of economic growth and carbon emissions reductions would differ among LCCs with different administrative levels, influencing cities' natural population growth differently. For instance, Yan et al. (91) found that the LCCP policies implemented in developed LCCs would more potentially reduce air pollution, driven by heightened awareness of personal health and environmental protection. Hence, LCCP policies are more likely to contribute to natural population growth by lowering the urban mortality rate in developed LCCs.

Interestingly, technological innovations brought by LCCP policies are not limited to agriculture (e.g., food supply) or transportation. Based on Yuan and Pan (10), LCCP policies require local enterprises to engage in technological innovations and stick to the sustainable operating paradigm. Consequently, local enterprises would promote cleaner production and comprehensive waste utilization (92) and restrain carbon emissions of particular LCCs. Based on the findings of section 2.2, the carbon emissions reductions brought by technological developments would and human health outcomes [Haines et al. (77, 92)] and contribute to natural population growth by reducing the local mortality rate. However, Yuan and Pan (10) also highlighted that the positive impacts of technological innovation brought by LCCP policies would only influence carbon emissions in the short term, which requires further investigations to discuss the relationships between LCCP policies and natural population growth.

LCCP policies can also achieve carbon emissions and optimize land utilization patterns by controlling land transfers (37). For instance, Lin et al. (48) empirically proved that the local governments of LCCs would withdraw the existing land of heavily polluting enterprises to optimize environmental conditions and facilitate sustainable development. As highlighted by section 2.2, the migration and food supply would be developed when the balance between economic growth and citizens' quality of life is optimized (70), and hence, LCCP policies would contribute to natural population growth.

3. Model, variables, and data sources

3.1. Model

DID is a classic model for estimating the impact of external shocks (89), which can greatly reduce endogeneity issues. Noted Liu and Xu

(94), based on the approval time of Lowcb (Note: in formulas, LCCP policy is presented as Lowcb), the cities implementing LCCP policies are the experimental group, and the remaining cities are the control group. Among them, the setting of the experimental group is based on the "Notice of the National Development and Reform Commission on Conducting Pilot Work in Low Carbon Provinces and Cities." The DID model is set as follows:

$$Birdea_{it} = \alpha_0 + \alpha_1 Lowcb_{it} + \alpha_2 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \quad (1)$$

$Birdea_{it}$ represents the natural population growth rate. $Lowcb_{it}$ represents the dummy variable for the low-carbon city pilot. Among them, the experimental group is taken as 0 before the implementation of the policy, and 1 after the implementation, and all the control groups are taken as 0. X_{it} represents the control variables, λ_t and μ_i represent the year-fixed effect and city-fixed effect, respectively, and ε_{it} represents the random disturbance term.

This paper also performs a parallel trend test based on the coefficient of dynamic effect based on the DID model. The model is set up as follows: $Lowcb^k_{it}$ represents whether the sample of city i and year t is the kth year from the implementation of the policy.

$$Birdea_{it} = \alpha_0 + \sum_{k=-8}^{8} \alpha_{1,k} Lowcb^k_{it} + \alpha_2 X_{it} + \lambda_t + \mu_i + \varepsilon_{it} \quad (2)$$

This paper studies the dynamic effect of each 8-year period before and after the policy, and the remaining variables have the same meaning as in the benchmark model. The confidence interval includes 0 when no significant difference exists between the experimental and control groups. The confidence interval does not include 0 when there is a significant difference between the experimental and control groups.

3.2. Variables

3.2.1. Independent variable

In this paper, LCCP is used as the core independent variable. Effective environmental regulations positively affect people's physical and mental health by improving the ecological environment, which in turn affects the natural growth rate of the population. Most studies [e.g., (76)] that have been conducted focus on the effects of environmental regulations or carbon emissions on mortality. However, limited studies have integrated measures of the effects on the natural population growth rate. As an important component of the population birth rate, improving the ecological environment also increases people's fertility and intention.

3.2.2. Dependent variable

The natural population growth rate is selected as the dependent variable in this paper, which is an important indicator of the rate of population growth and the development of population plans (57). The natural population growth rate equals the birth rate minus the mortality rate. The birth rate depends mainly on people's fertility and willingness to have children. The mortality rate mainly depends on the economic status, ecological environment, medical conditions and other uncontrollable contingent factors. The mortality rate is widely applied to measure population growth in previous studies (95), while in this paper we consider both the birth rate and the mortality rate which aims to provide a more comprehensive view for measuring the population growth.

3.2.3. Mechanism variable

This paper examines the transmission path of LCCP affecting the natural population growth rate from both macro and micro perspectives. In particular, green space is adopted as the mechanism variable for the measurement on the macro level. The impact of LCCP policies on citizens' physical health (Health) and mental health (Confi) is assessed as the examination on the micro level. The objective is to determine whether LCCP policies mitigate the adverse effects of limited green area accessibility and subsequently influence natural population growth. The self-rated "healthy" or "very healthy" in the questionnaire is considered as physically healthy. On the contrary, it is physically unhealthy. The questionnaire with 'little or no loss of confidence in oneself' is considered as psychologically healthy. On the contrary, it is psychologically unhealthy.

3.2.4. Control variable

In addition to the explanatory variables, other external factors may also affect the explained variables. If the effects of these potential factors are ignored, the regression results may be biased. Therefore, five control variables are selected in this paper: (1) Education level (Teastu), measured by the teacher-student ratio, and the higher the level of education, the lower people's willingness to have children, which reduces the natural growth rate of the population (96). (2 and 3) Industrial structure (Gdp2p and Gdp3p) is measured by the share of secondary and tertiary industries to GDP. As mentioned in the literature review, the developments of secondary and tertiary industries contradict the natural population growth (45), which needs to be empirically tested; (4) economic development level (Gdpreaave), measured by real *per capita* GDP. In economically developed regions, people have higher material living standards and lower population mortality rates (97). It can also potentially examine whether the incomes would facilitate rural–urban migration (74), which is emphasized in the literature review; (5) the level of Internet development (Intpop), measured as Internet coverage. Chen and Liu (98) find that internet development significantly promotes people's health, thereby promoting the natural growth rate of the population. To assess the impact of LCCP policies on natural population growth through the influence on the living environment, we introduced a variable green area (Green) apart from self-rated health (Health) and mental health (Confi) above. Micro control variables in the mechanism analysis section include gender, type of household, age, whether or not drinking alcohol, whether or not smoking, and whether or not having a job.

3.3. Data source

Considering the availability and accuracy of data, this paper is based on the data of 287 prefecture-level cities in China from 2003 to 2019 for research and analysis. The relevant data are mainly from the China Urban Statistical Yearbook, the China Urban and Rural Construction Statistical Yearbook and the China Labor-force Dynamics Survey (CLDS). For missing values, this paper uses interpolation to fill in the values by Stata. The descriptive statistics of the main variables involved are shown in Table 1.

4. Empirical results

4.1. Impact of LCCP policies on natural population growth

This paper uses the DID method to study the impacts of LCCP on the natural population growth rate, and the results are shown in Table 2. The coefficient of LCCP is positive when city and year fixed effects are included in column (1)—control variables are not included. It indicates that the natural population growth rate in low-carbon pilot cities increases after the policy is implemented compared to non-pilot cities. In other words, implementing the LCCP helps improve the natural population growth. There is no significant change in the promoting effect of LCCP on the natural population growth rate when the control variables of social level and economic level are, respectively, added in columns (2) and (3). Compared to the previous empirical findings, the coefficient of LCCP decreases after the inclusion of control variables, indicating that the social and economic level control variables affect the natural population growth rate to some extent. The coefficient of the core explanatory variable increases when all control variables (except fixed effects) are added in column (4). The coefficient of LCCP is significantly positive at the 1% level when all control variables and fixed effects are included in column (5). It can be seen that the higher the level of education, the lower the natural population growth rate. The higher the Internet coverage, the level of industrial structure and the real *per capita* GDP, the higher the natural population growth rate. Additionally, the inclusion of control variables raises the adjusted R^2, indicating that the selected control variables are effective.

4.2. Robustness test

4.2.1. Replacement of model and sample

The following tests are conducted in this paper to ensure sound robustness of the results. Since policies may have time lags, this paper first lags LCCP by one and two periods, respectively, and then performs DID regressions. According to the results in columns (1) and (2) of Table 3, the promoting effect of LCCP on the natural population growth rate increases as the number of lags increases. It indicates that LCCP has a greater promoting effect on natural population growth over time.

Second, cities and years were clustered separately in the regression. When clustering cities, it is assumed that the years of the same city are disturbed by common factors, and the random disturbances between different cities are not correlated. When clustering the years, it is assumed that the cities of the same year are disturbed by common factors, and the random disturbances between different years are not correlated. From the results in columns (3) and (4), it is clear that LCCP still significantly affects the natural population growth rate. When adding clustering standard errors, the assumed conditions are stricter, resulting in a decrease in significance.

Next, municipalities directly under the central government and provincial capitals are excluded. Compared with other prefecture-level cities, cities with higher administrative levels have different carbon emission control systems, fertility subsidy policies, and health care coverage. To eliminate the interference of this specificity, this paper regresses using the sample without municipalities directly under the central government and provincial capitals. The results in column (5) show that these cities with special administrative levels basically do not change the positive correlation between LCCP and natural population growth rate. Due to the higher health level of cities with higher administrative levels, the marginal utility of LCCP policies is smaller.

Finally, the core explanatory variable is replaced. Since carbon emission trading pilot and PLLC have similar policy impacts, this paper also replaced the DID variable to consider eight provinces and cities (e.g., Beijing, Tianjin, Shanghai, Chongqing, Shenzhen, Guangdong, Hubei, and Fujian) as the experimental group. The results are shown in column (6). It can be seen that the carbon emissions trading pilot is significantly and positively related to the natural population growth rate. It is because the carbon emissions trading pilot improves carbon efficiency and, to some extent, promotes low-carbon goals' achievements.

TABLE 1 Descriptive statistics of variables.

Variable	Description	Unit	*N*	Mean	Std.Dev.	Min	Max
Birdea	Natural population growth rate	‰	4,879	5.626	4.743	−6.700	20.100
Lowcb	LCCP policies	--	4,879	0.173	0.378	0.000	1.000
Teastu	Teacher-student ratio	Ratio	4,879	0.072	0.017	0.041	0.125
Gdp2p	Secondary industry to GDP	%	4,879	47.441	10.949	19.760	77.220
Gdp3p	Tertiary industry to GDP	%	4,879	38.585	9.358	17.330	68.560
Gdpreaave	Real *per capita* GDP	Deflated	4,879	1.993	2.243	0.058	11.607
Intpop	Internet penetration rate	Household/100 people	4,879	14.489	14.475	0.543	76.685
Green	Garden green area	km^2	4,879	60.073	121.068	1.780	916.740
Health	Self-rated health	--	16,767	0.608	0.488	0.000	1.000
Confi	Mental health	--	16,767	0.690	0.462	0.000	1.000

TABLE 2 DID regression results.

	(1)	(2)	(3)	(4)	(5)
Lowcb	0.7998*** (0.1887)	0.7023*** (0.1899)	0.7679*** (0.1891)	1.0282*** (0.2268)	0.7167*** (0.1893)
Teastu		−17.9385** (8.4244)		−96.0471*** (5.6673)	−15.5957* (8.7038)
Tntpop		0.0595*** (0.0090)		0.0213*** (0.0082)	0.0508*** (0.0103)
Gdp2p			0.0899*** (0.0184)	0.0011 (0.0086)	0.0981*** (0.0186)
Gdp3p			0.0973*** (0.0295)	−0.0138 (0.0130)	0.0971*** (0.0296)
Gdpreaave			0.3084*** (0.0368)	0.1832*** (0.0351)	0.2242*** (0.0398)
Constant	5.4974*** (0.0576)	5.9384*** (0.5816)	−3.1506 (1.9172)	12.1800*** (0.8602)	−2.9638 (2.2409)
Year FE	Yes	Yes	Yes	No	Yes
City FE	Yes	Yes	Yes	No	Yes
N	4,879	4,879	4,879	4,879	4,879
Adjusted R^2	0.5653	0.5714	0.5721	0.0867	0.5761

Robust standard errors are corrected in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 3 Results of model and sample replacement.

	(1)	(2)	(3)	(4)	(5)	(6)
L. Lowcb	0.5828*** (0.2021)					
L2. Lowcb		0.8444*** (0.2139)				
Lowcb			0.7167** (0.3076)	0.7167* (0.3719)	0.5875*** (0.2100)	
Cbtrad						3.2745*** (0.3228)
Constant	−3.2880 (2.4182)	−3.8538 (2.4687)	−2.9638 (4.0820)	−2.9638 (3.1993)	−6.3193*** (1.7609)	−1.8015 (2.2063)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4,592	4,305	4,879	4,879	4,352	4,879
Adjusted R^2	0.5836	0.5918	0.5760	0.5760	0.5895	0.5868

Robust standard errors are corrected in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

4.2.2. Parallel trend test

If there is a certain difference between the processing group and the control group beforehand, then using DID results can no longer represent the net effect of the policy. The assumption of parallel trends is a prerequisite for conducting DID analysis. In order to visually test the effect of LCCP on the natural population growth rate, the dynamic effect coefficient of this policy shock is estimated in this paper, and the results are shown in Figure 2. It can be seen that before the implementation of LCCP, there was no significant difference between the experimental and control groups from the perspective of the natural population growth rate. The confidence interval does not contain 0 within 4 years after the policy implementation. The empirical findings above indicate that the data used in this paper satisfy the parallel trend assumption and that there is a 4-year lag in the effect of LCCP on the natural population growth rate, further demonstrating the robustness of the previous results. It may be due to the time required to implement LCCP and the time lag for the full effect of the policy.

4.2.3. Placebo test

To further test the validity of LCCP, this paper uses the placebo test as follows. First, this paper randomly sorts the experimental group and policy time 1,000 times simultaneously to obtain 1,000 simulated policy variables. The simulated variables are sequentially put into the original regression model to test whether the mean of these effects is equal to 0 to determine whether the results of the benchmark regression are obtained by chance. The coefficients and *p*-values of the simulated policy effects are shown in Figure 3. As can be seen, the true effect of the benchmark regression is located at the end of the right tail, which indicates that the results of the benchmark regression are not found by chance.

4.2.4. PSM-DID

Since LCCP is based on local declarations and the representativeness of pilot layouts, the policy is not completely randomized but is closely related to factors such as the economic development status of the city. This paper uses PSM to obtain a control group corresponding to the experimental group to avoid the bias of DID estimation results. The matched results are shown in Table 4, and there is no significant difference in the covariate characteristics between the experimental and control groups. As expected, the unmatched results show significant differences between the experimental and control groups in terms of education level, industrial structure, real *per capita* GDP, and Internet coverage.

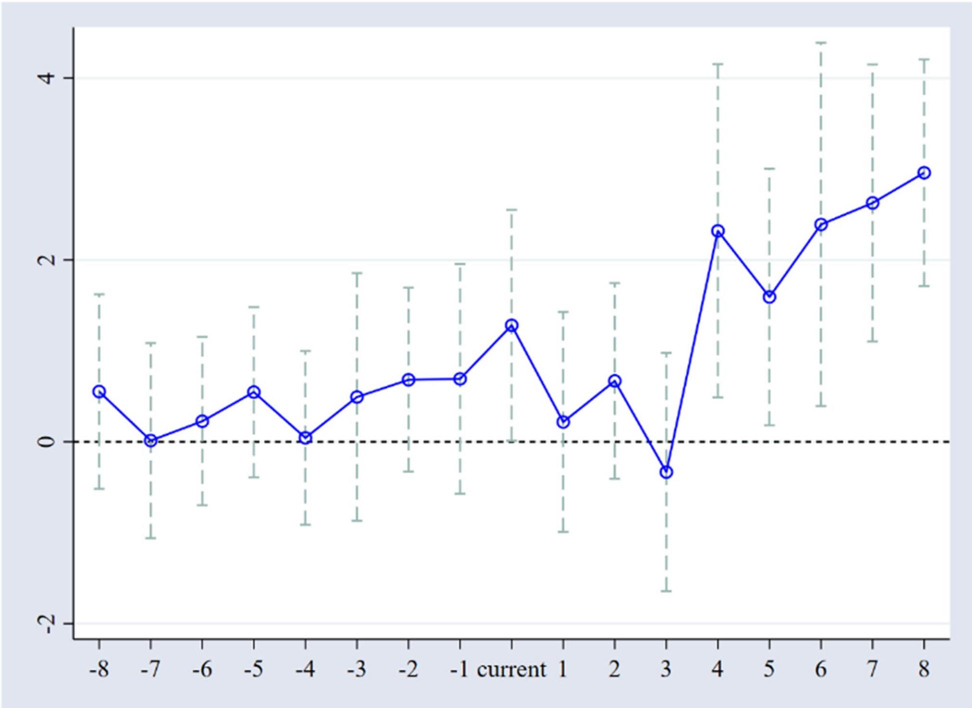

FIGURE 2
Parallel trend test results.

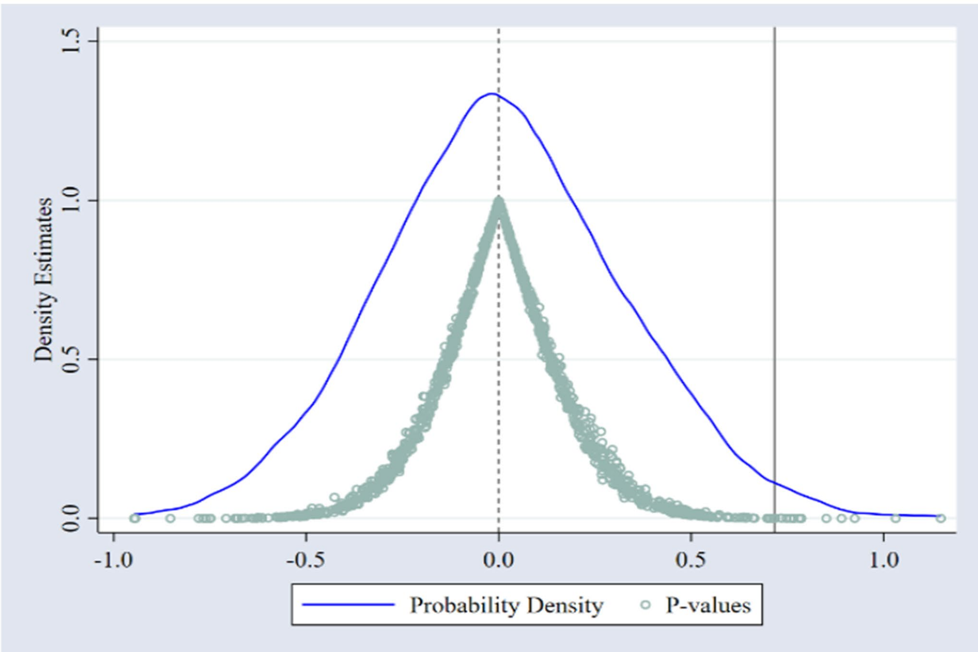

FIGURE 3
Placebo test results.

According to Figure 4, the kernel density functions before and after matching are much closer, largely reducing the interference caused by selection bias.

After excluding selectivity bias, this paper performs regressions using samples with no null weights, respectively meeting the common support assumption and frequency weighting. The results are shown

TABLE 4 Balance test results of matching characteristic variables.

Variable	Unmatched matched	Mean		%Bias	*t*-test	
		Treated	Control		t	*p*>|t|
Teastu	U	0.074	0.071	14.8	5.14	0.000
	M	0.073	0.074	−2.3	−0.75	0.452
Gdp2p	U	47.124	47.729	−5.5	−1.87	0.061
	M	47.439	47.318	1.1	0.36	0.720
Gdp3p	U	41.113	36.711	46.5	16.24	0.000
	M	40.421	40.162	2.7	0.84	0.400
Gdpreaave	U	2.236	1.887	13.8	4.79	0.000
	M	2.153	2.146	0.2	0.09	0.931
Intpop	U	18.452	11.728	44.3	15.83	0.000
	M	16.561	17.282	−4.8	−1.45	0.146

in columns (1)–(3) of Table 5. Compared with the benchmark regression, the coefficient of LCCP is smaller in the results of PSM-DID, indicating that the benchmark regression overestimates the effect of LCCP on the natural population growth rate, but this does not affect the robustness of the conclusions.

4.2.5. Bacon decomposition

The problem of bias in staggered DID with Two-Way Fixed Effects (TWFE) has been discussed in the literature (99). Since the treatment effects of TWFE regressions are typically heterogeneous across experimental groups or policy times, the problem of using bad treatment groups and the appearance of negative weights may arise. Therefore, this paper refers to the Goodman-Bacon (100) decomposition of the DID estimator to examine the degree of bias in the staggered DID estimates under TWFE. The results are shown in Table 6. The first round decomposition included all control variables, and the anticipated good treatment effect was 1.0809 with a weight of 0.8057. The coefficient of LCCP remains significant in the second round of detailed decomposition without any control variables, and the anticipated good treatment effect was 1.0589 with a weight of 0.8477. Since the estimates of the bad treatment effect are all negative and the weights are small, the core findings of this paper can be considered robust.

4.2.6. Modified DID estimation

This paper uses the two-stage estimation framework to identify, removing group and period effects in the first stage and obtain the average treatment effect in the second stage (101). The results are robust when the treatment effects are staggered and heterogeneous. According to the regression results in Table 7, LCCP still has a significant promoting effect on the natural population growth rate, indicating the robustness of the results from the benchmark regression.

4.3. Robustness test

The results suggest that China's LCCP policies significantly promote natural population growth. However, do the effects of population growth under the influence of other policies still exist? Are there significant differences between different environments and regions? To this end, the following heterogeneity analysis is conducted in this paper.

4.3.1. Heterogeneity of healthy city pilot

In this paper, firstly, according to the "Notice of the National Office of Health Care on the Piloting of Healthy Cities" issued by the National Administration of Disease Prevention and Control in 2016, the cities implementing the healthy pilot are used as the experimental group, and other cities are used as the control group. The dummy variable of the healthy city pilot interacted with LCCP and then regressed. The results in column (1) of Table 8 showed that the variable Lowcb * Healcity have a facilitative effect at the 1% significance level, indicating that in those cities that implemented both LCCP and the healthy pilot, the two policy effects are not conflicting or contradictory, but mutually reinforcing. The Healthy City Pilot has a synergistic effect with LCCP policies to some extent by continuously improving the natural environment, social environment, and health services.

4.3.2. Heterogeneity of health informatization

Then, according to the national health informatization development index in 2022, this paper sets the dummy variable corresponding to the Top 60 cities to 1 and the other cities to 0. The dummy variable interacted with LCCP and then regressed; the results are shown in column (2) of Table 8. In cities with high levels of health informatization, LCCP can better promote population growth through good health system construction and application.

4.3.3. Regional heterogeneity

To further investigate the regional heterogeneity of LCCP policies, this paper divides the sample into four groups: Eastern, Central, Western, and Northeastern regions. The generated dummy variables interacted with LCCP, respectively, before regression. Among them, the Northeast region is used as the control group. The results in column (3) of Table 8 showed that LCCP policies have the largest promoting effect on the natural population growth rate in the East, followed by the Central and Western regions. It may be because the scale of carbon emissions in the industrial development process is larger in the Eastern region. Hence, LCCP policies had a stronger emission reduction effect in this region and a stronger promoting effect on the natural population growth rate. In contrast, there are

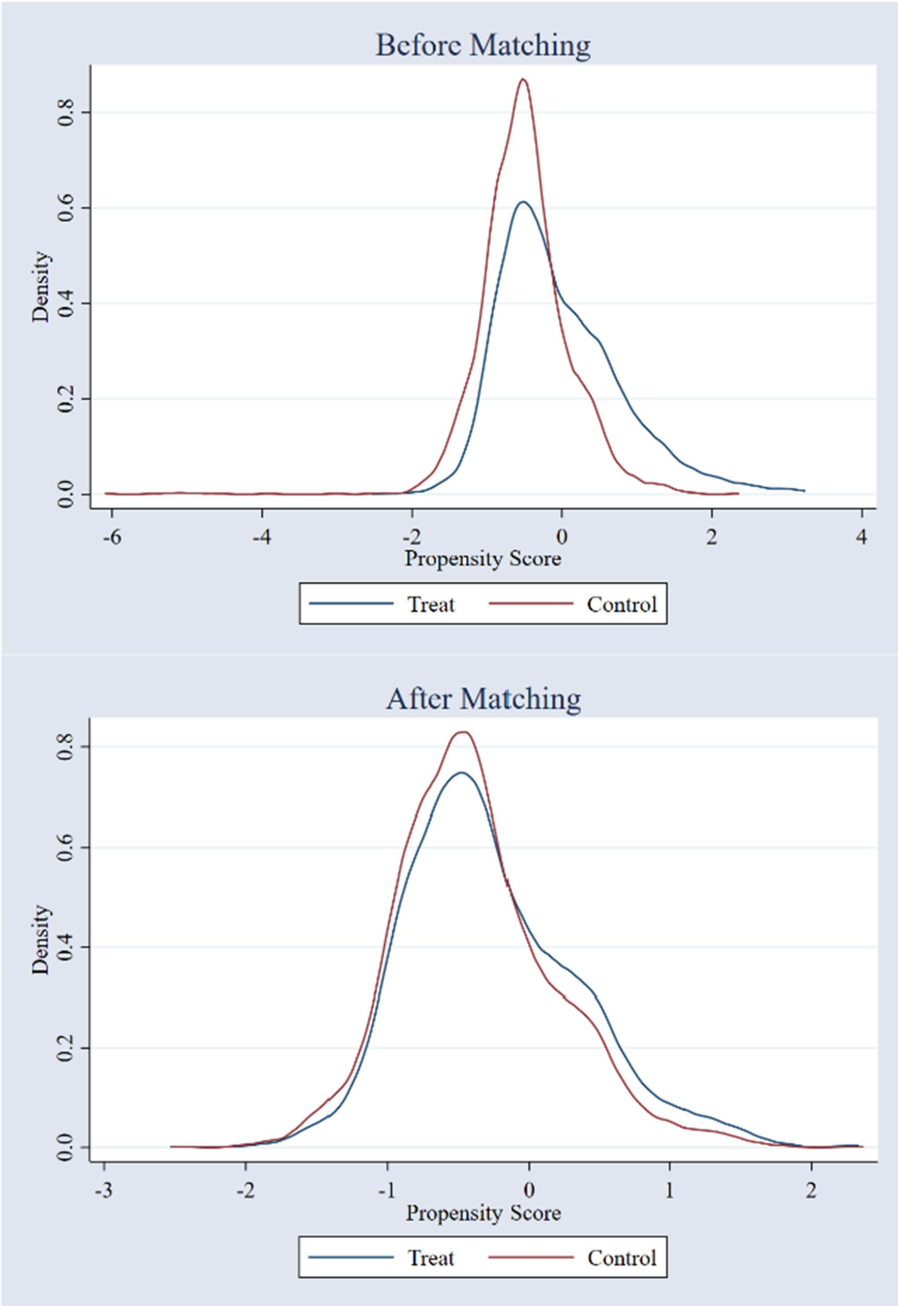

FIGURE 4
Nuclear density distribution before and after matching.

fewer industrial enterprises in the Central and Western regions, so the effect of LCCP on the natural population growth rate is limited.

4.3.4. Heterogeneity of administrative levels

Cities at different administrative levels have different policy implementation plans. In general, cities with higher administrative levels have more resources, and the intensity of their policy enforcement may be higher. Therefore, the dummy variable interacted with LCCP and then regressed. Among them, the dummy variable corresponding to municipalities directly under the central government and provincial capitals is set to 1, and 0 for other cities. The results in column (4) of Table 8 indicate that the promoting effect of LCCP on the natural population growth rate is greater in cities with higher administrative levels, confirming the previous hypothesis.

4.3.5. Heterogeneity of development level

Finally, this paper generated interactions between LCCP policies and the dummy variable measuring the level of urban development based on the New Tier 1 Cities Institute's "2021 City Business Attractiveness Ranking" and a regression analysis was conducted. The corresponding dummy variable was set to 1 for Tier 1 and New Tier 1 cities and 0 for others. The results in column (5)

TABLE 5 PSM-DID regression results.

	(1)	(2)	(3)
Lowcb	0.3797* (0.2235)	0.5731*** (0.1927)	0.4591** (0.1991)
Constant	−7.0882*** (2.1404)	−3.7031* (2.1228)	−6.5732*** (1.7014)
Control variables	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
N	3,404	4,787	5,617
Adjusted R^2	0.5864	0.5777	0.6151

Robust standard errors are corrected in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 6 Bacon decomposition results.

First. considering control variables	Beta	Weight	Second. Without control variables	Beta	Weight
Estimate	0.7166** (0.3076)	1.0000	Estimate	0.8130** (0.3427)	1.0000
Treated	−0.5765	0.1609	Earlier vs. Later	−0.6012	0.1058
Within	−1.8424	0.0333	Later vs. Earlier	−0.4503	0.0465
Treated vs. never treated	1.0809	0.8057	Treated vs. never treated	1.0589	0.8477

Standard errors are in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

TABLE 7 Two-stage estimation results.

Coefficient	Std. Err.	Z	*P*>|z|	95% conf. interval
0.9878	0.3298	2.99	0.003	[0.3413, 1.6342]

TABLE 8 Heterogeneity analysis results.

	(1)	(2)	(3)	(4)	(5)
Lowcb	0.6376*** (0.1929)	0.3958* (0.2124)	−2.3736*** (0.3754)	0.5534*** (0.2086)	0.5335*** (0.2039)
Lowcb * Healcity	1.2276*** (0.4749)				
Lowcb * Healinf		1.3826*** (0.3468)			
Lowcb * East			4.3182*** (0.4481)		
Lowcb * Mid			3.4104*** (0.4920)		
Lowcb * West			2.6294*** (0.4608)		
Lowcb * Admi				0.9225** (0.3738)	
Lowcb * Tier					1.3136*** (0.3905)
Constant	−3.1377 (2.2267)	−2.7503 (2.2430)	−1.0719 (2.2425)	−3.0450 (2.2302)	−2.9627 (2.2400)
Control variables	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes
N	4,879	4,879	4,879	4,879	4,879
Adjusted R^2	0.5765	0.5772	0.5827	0.5764	0.5767

Robust standard errors are corrected in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

of Table 8 showed that the promoting effect of LCCP on the natural population growth rate is greater in cities with higher development levels. In recent years, the natural population growth rate has been low due to the high cost of childbirth in Tier 1 cities. And implementing LCCP policies can reduce the gap in population growth between different regions.

5. Mechanism analysis

The results of this paper show that when cities implement LCCP policies, the natural growth rate of the local population increases, and how it works. Next, this paper examines macro and micro perspectives, specifically, the greening rate and physical and mental health. The

TABLE 9 Mechanism analysis results.

	Green area	Health	Confidence
Lowcb	19.1227*** (2.6996)	1.2280*** (0.3814)	0.9459*** (0.3662)
Constant	66.1088*** (14.4246)	2.0476*** (0.3482)	0.3362*** (0.3934)
Control variables	Yes	Yes	Yes
Year FE	Yes	No	No
City FE	Yes	No	No
City#Year FE	No	Yes	Yes
County FE	No	Yes	Yes
N	4,879	16,767	16,767
R^2	0.9081	0.1519	0.0970

Robust standard errors are corrected in parentheses. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

results in Table 9 show that LCCP policies expand the urban green area. Increasing green space reduces the probability of stress-related problems, depression, and other mental illnesses. In addition, Richardson and Mitchell (102) find that an increase in green space areas reduces mortality rates from cardiovascular and respiratory diseases. On the other hand, LCCP policies improve people's mental health and reduce the tendency of unnatural death, such as suicide. Research has shown that depression is an important factor affecting fertility and the number of children (103). People gain a sense of well-being while also increasing their willingness to have children. It has been shown that reducing carbon emissions has saved many people from early death or enabled people to live longer. The improvement of physical health through the LCCP policies has also improved fertility.

6. Discussion and conclusion

Based on the existing studies [e.g., (14, 83)], developing and implementing LCCP policies are the keys to the low-carbon economy and natural population growth plays a crucial role in economic growth and the environment (28, 56). Hence, this research further investigates the impacts of LCCP policies on natural population growth since there is still a lack of research exploring the impact mechanisms of LCCP policies (37) from the LCCs' perspectives (36).

6.1. Theoretical implications

This research contributes to knowledge by (1) building and enriching a framework of LCCP policies' impact mechanisms and (2) theoretically emphasizing the features of LCCP policies from the perspective of LCCs' natural population growth.

First, this research empirically found that the LCCP policies would influence LCC's natural population growth by impacting (a) economic factors, (b) political factors, (c) technological factors, and (d) the living environment, which builds and enriches the under-investigated impact mechanism of LCCP policies.

(a) This research aligns with previous studies [e.g., (36)] by supporting that the LCCP policies promote natural population growth by optimizing LCCs' industrial structure and the subsequent increase in per-capita income. This finding highlights the theoretical significance of optimizing industrial structure in establishing and developing LCCs. After all, the optimization of the industrial structure, as indicated by the rising contribution of the secondary and tertiary industries to the GDP, fosters employment opportunities in both secondary and tertiary industries (104), thereby accelerating rural–urban migrations by making the LCCs more attractive (73, 74). However, this research does not empirically establish the negative correlation between the development of secondary and tertiary industries and population growth, as argued by Deng et al. (45) and Wu et al. (44). A possible explanation noted by Shi et al. (105) suggests that scientific agricultural cultivation promotes effective land utilization, which would reduce dependence on cultivated land by the population.

(b) From the political perspective, this research highlights the varied impacts of LCCP policies on regional population growth, considering factors such as the administrative levels (90) and geographical locations (85) of LCCs. Significantly, this research extends the above research directions by further explaining the underlying mechanisms through how LCCP policies influence population growth, with a focus on regional differences. Consistent with previous studies [e.g., (87, 89)], this research suggests that the LCCP policies affect China's Eastern and Western regions differently. The intensity of LCCP policies in Eastern China would be higher to align with the large carbon emissions basis and a greater willingness for industrial structure transformation (34, 88). Conversely, the LCCs in Western China are more likely to compromise with economic growth due to limited funding and policy leverage, as Fu et al. (89) noted. Consequently, this research empirically provides that the LCCP policies have more pronounced effects on improving air conditions in developed LCCs in Eastern China than in Western regions. Hence, the LCCP policies in Eastern China are more likely to contribute to population growth by reducing mortality rates.

(c) This research enhances the framework of the impact mechanisms of LCCP policies on natural population growth by proposing additional technological factors. By extending the technological factors driving population growth mentioned by existing papers which focus on food supply (68), transport system development (20) and sustainable operating paradigm (10, 33), this paper empirically found that the Internet penetration rate also positively impacts LCCs' natural population growth. A possible explanation would be given by Bessière et al. (106), who mentioned that the Internet's growth makes obtaining medical information and building interpersonal communications easier. Consequently, the informal support offered by the Internet (107) would reduce mortality by promoting better public healthcare and mitigating the negative effects of depression.

(d) This research provides a novel empirical approach proving the positive impacts of an increasing greening rate brought by LCCP policies on natural population growth. Unlike previous studies [e.g., (25, 108)] based on the ratio of urban green areas to the population, this research examines the self-rated physical and mental health of the citizens residing in Chinese prefecture-level cities. According to our empirical investigation, this research demonstrates that the increased green areas brought by LCCP policies alleviate individuals' pressures, reduce the likelihood of depression, and consequently enhance overall health conditions and well-being. This finding further consolidates the existing viewpoints from studies [e.g., (91, 108)], underscoring that LCCP policies enhance urban green areas, leading to an improved living environment and reduced carbon emissions.

Second, to further serve the impact mechanisms of LCCP policies, this research theoretically proposes features of LCCP policies which should be cautiously considered during implementation on the LCC basis. This research empirically found a 4-year lag in the effects of LCCP policies on LCC's natural population growth, which should be seen as a challenge in implementing policies (109). Moreover, as mentioned earlier, regional differences should be cautiously considered as this paper empirically found different carbon reduction outcomes when the LCCP policies are implemented in China's LCCs in different regions. Additionally, this research empirically found that the LCCP policies can be combined with other supporting public policies [e.g., emission trading (110) and healthy city pilot (111)] to further facilitate LCCs' natural population growth.

6.2. Practical guidance

This research makes substantial practical contributions to sustainable development and the promotion of rational population growth by further explaining the insights into the impact mechanisms of LCCP policies for China and other developing countries in similar development stages. First, this research recommends that both central and local governments in China prioritize the process of industrial structure optimization. LCCs are expected to develop cities' attractiveness by increasing the proportion of the tertiary industry and employment level. For instance, it is suggested to promote the GDP contributions of service-relevant industries and encourage rational rural–urban migrations to make the LCCs more attractive. This approach applies not only to the more developed Eastern but also to the Western regions of China. Furthermore, the recommendation above also holds value for other developing countries that share similar development stages with China.

Second, this research helps policymakers in China and other developing countries to better understand that the formulation of LCCP policies should follow LCCs' regional characteristics and administrative levels to make the goals and processes appropriate. For instance, this research recommends that the central government allocates increased policy support to the LCCs in underdeveloped areas (e.g., Western China). This support can take the form of financial investment in low-carbon infrastructures and the provision of tax breaks, aiming to alleviate concerns among underdeveloped areas regarding the sole pursuit of economic development. Moreover, this research suggests that the LCCs' governments to further develop LCCP policies' supporting policies to optimize their effects on sustainable development and public health services, such as developing emissions trading systems and healthy city pilot policies. Meanwhile, the LCCs' governments and other developing countries should recognize and mitigate the time lag effects of LCCP policies. For instance, the LCCP policy design should be flexible to accommodate potential changes during implementation. Additionally, establishing a robust real-time monitoring evaluation system is crucial to identify the time-lag effects and to facilitate timely corrective actions.

Third, this research proposes that central and local governments, along with the enterprises in China, further develop low-carbon-relevant technological innovations when designing LCCP policies. This recommendation enables an in-depth promotion of sustainable development and rational population growth. Suggested technological innovations include optimizing transportation infrastructure, fostering cleaner production approaches, and undertaking comprehensive waste utilization. Moreover, facilitating technological innovations in agriculture is essential to increase the utilization effectiveness of cultivated land to better meet the population's needs. Significantly, to highlight the importance of more effectively utilizing the Internet, this paper suggests that China's central and local governments proactively establish official or authorized online healthcare communities or platforms, such as smartphone applications based on big data. These platforms can provide citizens with a wealth of medical information and improve the accessibility to quality public healthcare services, thereby complementing the implementation of LCCP policies.

Fourth, this paper recommends that the governments of LCCs in China and other developing countries enhance citizens' physical/mental well-being and living environment by expanding the urban green spaces. However, it is crucial that the selection of green space locations aligns with scientific city planning principles. For instance, it is suggested to avoid establishing green spaces in close proximity to heavily trafficked areas. Furthermore, supporting policies promoting air pollution prevention and fostering a green lifestyle should be advocated to reinforce the positive impact of green spaces. By enhancing citizens' physical/mental well-being, the LCCs in China and other developing countries can unlock the potential of LCCP policies and foster rational natural population growth.

6.3. Limitations and recommendations

Despite crucial insights proposed by this research, this research has limitations which should be further explored in future studies. First, as a China-focused study, it cannot always reflect the features of LCCs and LCCP policies of other countries in the developing or developed world. Hence, further studies are required to support other developing countries' sustainable development and rational population growth. Second, although this research investigated the impacts of LCCP policies on LCCs' natural population growth, the discussion on how LCCP policies should be implemented to achieve a sound/appropriate natural population growth rate should be further conducted in the future. For instance, this research recommends that optimizing industrial structure is crucial. However, this research also highlights the need to further explore the relationship between the development of secondary/tertiary industries and population growth, considering the population's dependence on cultivated land. Furthermore, this research acknowledges the time-lag effects in policies, which the existing studies have substantiated. Consequently, further studies are expected to concentrate on mitigating the time-lag effects, ensuring timely responses to potential changes or challenges that may arise while implementing LCCP policies. The potential research directions above will contribute to the effective design and implementation of LCCP policies. Third, since the framework of the impact mechanisms of LCCPs is newly built and limited studies have touched on this aspect previously, the richness and comprehensiveness of the framework can be further investigated in the future, which reveals other future research directions. For instance, future research can measure other influential factors which impact the relationship between LCCP policies and natural population growth from the perspective of LCCs.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YZ and MZ provided the research ideas, conceived the research model, and were responsible for data collection and analysis. SW produced the introduction, literature review, discussions, and conclusion and edited the manuscript. LW was responsible for research idea and critically revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

MZ was employed by China National Gold Group Gold Jewellery Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Under the different sectors: the relationship between low-carbon economic development, health and GDP

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Developing a modern low-carbon economy while protecting health is not only a current trend but also an urgent problem that needs to be solved. The growth of the national low-carbon economy is closely related to various sectors; however, it remains unclear how the development of low-carbon economies in these sectors impacts the national economy and the health of residents. Using panel data on carbon emissions and resident health in 28 province-level regions in China, this study employs unit root tests, co-integration tests, and regression analysis to empirically examine the relationship between carbon emissions, low-carbon economic development, health, and GDP in industry, construction, and transportation. The results show that: First, China's carbon emissions can promote economic development. Second, low-carbon economic development can enhance resident health while improving GDP. Third, low-carbon economic development has a significant positive effect on GDP and resident health in the industrial and transportation sector, but not in the construction sector, and the level of industrial development and carbon emission sources are significant factors contributing to the inconsistency. Our findings complement existing insights into the coupling effect of carbon emissions and economic development across sectors. They can assist policymakers in tailoring low-carbon policies to specific sectors, formulating strategies to optimize energy consumption structures, improving green technology levels, and aiding enterprises in gradually reducing carbon emissions without sacrificing economic benefits, thus achieving low-carbon economic development.

KEYWORDS

carbon neutrality, industry low-carbon economy, health, greenhouse gases, economic growth

1. Introduction

The contradiction between the environment, health, and the development of the economy has been a global concern (1, 2). Reducing carbon dioxide (CO_2) emissions is internationally recognized as one of the effective ways to achieve sustainable development (3, 4). Since the Industrial Revolution, carbon emissions have been increasing annually with technological and economic development. Large amounts of carbon emissions result in increasing global warming problems, rising sea levels, mass extinction of species rapidly, forest fires, and the frequent occurrence of severe weather (5, 6). Due to the inevitability of economic development and the

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drawbacks of carbon emission, low-carbon economic development has always been an important research direction for scholars around the world (7, 8). China undoubtedly plays a significant role among carbon emitters, its energy consumption structure and efficiency improvement can greatly contribute to enhancing global environmental quality (9, 10). Currently, China's economy is undergoing a transition toward intelligent, green, and low-carbon development (8, 11), and the urgent need for a low-carbon economy has been reflected in China's policies (12). Previous research has demonstrated that a low-carbon economy is necessary for achieving sustainable development (13, 14). The sustainable development policies proposed by the Chinese government have achieved some positive results, such as slower growth in carbon emissions (13). However, the total carbon emissions of some sectors continue to grow, and the problem of high carbon emissions is far from being fundamentally solved. At the same time, due to differences in energy consumption types, economic development levels, and impacts on residents' health, there are different sustainable development layouts between various sectors in China. It is worth studying how sectors control carbon emissions while promoting coordinated economic growth and improving residents' health. Therefore, it is necessary to conduct an in-depth analysis of China's low-carbon economic development by sectors, to understand the potential for sustainable development in different sectors.

Low-carbon economic development refers to economic development patterns that reduce the consumption of highly carbon-content energy and carbon emissions without hindering economic and social development (15). The Chinese government has made it clear that the key to improving the development of China's low-carbon economy depends on four major industries: electricity, industry, construction, and transportation (16). Based on this, and considering our research focus, the industry, construction, and transportation sectors are identified as our research subjects. The industrial sector refers to the production activities of society that exploit natural resources and process raw materials, construction refers to civil engineering and housing construction activities, and transportation refers to the business activities of using means of transport to move goods or passengers and transfer their spatial location (17). According to the China Energy Statistical Yearbook (18), China's total economic output and energy consumption continued to grow between 2005 and 2019. In 2005, 1.40 tons of standard coal were consumed for every 10,000 yuan of GDP growth, compared with 0.55 in 2019 (18). Although the energy consumption required to increase the total unit economy decreases, with the development of the economy, the total energy consumption increased from 250.835 million tons of standard coal to 447.597 million between 2005 and 2019, and the total carbon emissions increased by 1.81 times. Conventional wisdom holds that increased energy consumption and carbon emissions have adverse effects on health. However, previous studies have shown either mixed or inconclusive findings regarding the relationship between health, economic growth, and carbon emissions (19, 20). Therefore, this study aims to investigate the impact of low-carbon economic development, identify important gaps in carbon emissions and economic development of different sectors, and examine how the development of low-carbon economies in different sectors affects health.

We provide a conceptual discussion on the development of a low-carbon economy, which outlines clear requirements for energy consumption, carbon emissions, and economic development. Previous studies have shown a strong two-way promotion relationship between energy consumption and carbon emissions, as well as between energy consumption and economic development (21, 22). However, there seems to be no broad consensus on the relationship between carbon emissions and economic development. Some studies argue that economic development is a double-edged sword: carbon emissions increase when the economy begins to develop, but when the economy reaches a certain level, it reduces carbon emissions (23–25). Other scholars do not support this opinion, arguing that the relationship between carbon dioxide and economic development varies depending on the choice of the study regions (26, 27). The debate over the relationship between carbon dioxide and economic development continues (28). Some studies have proposed that economic development has increased the carbon emissions of countries by changing people's consumer habits and encouraging the purchase of products with high carbon emissions. Other studies suggest that there is a different relationship between the economic development of different sectors and carbon emissions. For example, the development of the construction industry increases carbon dioxide emissions (29), while the development of tourism can have the opposite effect (30). Therefore, studying the relationship between carbon emissions of different sectors and economic development is helpful to find ways to efficiently achieve low-carbon economic development.

Compared to energy consumption, carbon emissions, and economic development, health is directly related to human beings and is an important driving force for research on low-carbon economic development. An increase in health problems can lead to disease, unemployment, and poverty (31, 32). According to the statistics of the Chinese Health Commission (33), the total per capita health expenditure in 2021 was 5348.1 yuan, and the total national health expenditure accounted for about 6.5% of GDP. Medical expenses have become a heavy burden for some families. Several studies have shown a significant relationship between health and carbon emissions (34, 35). Some suggest that carbon emissions harm health, for example, by raising the concentration of carbon dioxide (36) or the temperature (37, 38). Another partial literature argues that there is no relationship between carbon emissions and health, noting that there is no significant evidence suggesting that carbon emissions have an impact on short or long-term health (39). Additionally, after summarizing existing studies, we find that the health impacts of carbon emissions vary by sector (40, 41). For example, carbon emissions from the transportation sector mainly come from the combustion of fossil fuels, and reducing transportation can reduce the mortality rate of residents (Transport demand, harmful emissions, environment, and health co-benefits in China). The cement industry's carbon emissions mainly come from fossil fuel combustion, the process of converting limestone and reducing the use of cement can reduce the probability of respiratory diseases. However, there is rarely research that explored the relationship between health and carbon emissions across sectors. Therefore, investigating the relationship between carbon emissions and health in different sectors can provide valuable insights into the importance of low-carbon economic development for promoting health.

Previous studies have examined the relationships between low-carbon economic development, GDP, and health. However, most scholars use a region as a whole (42–44), analyzing the relationship between the overall low-carbon economic development and other variables, ignoring the large differences between sectors. Some studies

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have focused on specific sectors but do not take into account the impact of the relative sectors. In this study, we analyze panel data about 28 province-level regions in China from 2005 to 2019. To examine the long-term linear validity of the model, unit root tests and co-integration tests are employed. Regression analysis is conducted to quantify the relationship between low-carbon economic development, carbon emissions, health, and GDP in the industry, construction, and transportation sectors. The results show that: First, the health impact of carbon emissions is not significant, whether in industry, construction, or transportation. Second, low-carbon economic development plays a positive and significant role in health, while the construction sector is not included. Third, carbon emissions and low-carbon economic development could increase GDP, and the improvement effect of carbon emissions is generally higher than that of low-carbon economic development. Specific to sectors, the impact of low-carbon economic development in the industry and transportation on GDP is positively significant, but the impact is not significant in the construction sector.

Through this study, we aim to make the following contributions. One of our main theoretical contributions is revealing the differences in carbon emissions and low-carbon economic development across sectors. Then, through sector-to-whole and sector-to-sector comparisons, we achieve the relationship between carbon emissions, low-carbon economic development, health and GDP, and find differences and contradictions among them. Furthermore, one of our main practical contributions is to provide references for government-industry development planning. Our findings can assist governments in identifying sectors where economic investments and the actual outcomes of energy conservation and emission reduction are disproportionate. For example, we show that despite substantial investments aimed at achieving low-carbon development, the construction industry has limited positive impacts on health and GDP. This information can inform more targeted and effective decision-making in government policies. Another practical contribution is helping industrial, construction, and transportation enterprises understand the gap between sectors that develop a low-carbon economy, and providing a clear reference for their carbon reduction goals.

2. Literature review

2.1. Low-carbon economic development

The term “low-carbon economy” first appeared in the 2003 White Paper on the Power of Government in the UK (45). Subsequently, Mantoani and Osborne (46) propose that the intensification of the global greenhouse effect would inevitably interfere with the sustainable growth of the global economy. Therefore, it is necessary to use relevant market mechanisms and government intervention to comprehensively use various energy-saving and emission-reduction technologies to achieve higher energy efficiency, lower energy consumption, and lower carbon emissions in the development of the national economy. It is from this perspective that the definition of low-carbon economic development is derived. Low-carbon economic development has become one of the important indicators to judge the efficiency of energy conservation and emission reduction in a region. Researchers have successfully used the concept of low-carbon economic development between economic development and energy consumption and carbon emission levels at the national, regional (42–44), and industrial levels (47–49).

However, measuring the development of the low-carbon economy is a complex and controversial issue. A common practice is for scholars to establish an evaluation index system to judge the development of the low-carbon economy based on the data they have and the problems to be studied. Dang et al. (50) focus on the low-carbon economic development of Guangzhou, China, and use the SEM model to establish an evaluation index system from the perspectives of energy structure and efficiency, economy, and environment. Tao et al. (51) use the LEAP model to establish an evaluation index system for low-carbon economic development based on per-capita GDP, amount of energy consumption, energy structure, and amount of CO_2 emissions. Another approach usually appears in articles that do not focus on measuring low-carbon economic development, using existing model paradigms to judge the level of low-carbon economic development and do further research. For example, Liang et al. (52) use the Tapio decoupling model to analyze the decoupling state of Shenzhen and judge the development of the low-carbon economy by the degree of decoupling between carbon emissions and economic growth. The Tapio model calculates the ratio of changes in economic output to carbon emissions in energy-intensive sectors, and this method is also used in our study to measure low-carbon economic development. In addition, scholars have developed new machine learning algorithms to measure the development of low-carbon economies (53).

2.2. Influence of low-carbon economic development on health

Health is a fundamental issue in the field of social (54). According to classical economic theory, health is an important form of human capital and one of the crucial factors that promote economic development (55). In a study of health and economic development in the 20th century, Gallardo-Albarrán (56) finds that health is a significant cause of income variation during this period, particularly due to HIV, and that mortality rates increase in low- and middle-income countries. Du and You (57) propose that there is a positive and stable relationship between economic development and health; conversely, an increase in respiratory diseases can hinder economic development.

Although health contributes to economic development, it is vulnerable to influences (58, 59), such as economic and carbon dioxide. He and Qiu (40) analyze carbon emissions from different modes of consumer travel, including road, rail, waterway, and air transport. They find that reducing carbon emissions by reducing transportation volumes can also reduce deaths from related diseases due to air quality. When investigating the impact of carbon taxes on air quality, Li et al. (36) unexpectedly find that reducing carbon dioxide concentrations would also lead to fewer premature deaths. Dong et al. (37) find that carbon emissions have long-term adverse effects on human health. An increase of 1% in carbon emissions is associated with a 0.298% increase in outpatients and a 0.162% increase in inpatients, which is caused by the temperature increase resulting from increased carbon emissions. Goodman et al. (60) have another opinion, suggesting that poor health and illness are not independently related to CO^2 emissions. Alola (39) argues that there is no significant relationship between carbon emissions and health, either in the long or short term. Sarwar et al. (19) have similar results, where their study shows that the health impact of carbon emissions differed by the calculation methodology, with carbon emissions not significant for health in the fixed effect model and difference GMM, but significant in system GMM.

Considering the relationship between health and the economy, as well as health and the environment, the impact on health cannot be ignored when studying the development of the low-carbon economy. However, few existing studies have directly analyzed the health impacts of low-carbon economic development. Instead, most explore the relationship between low-carbon economic development and health from a low-carbon perspective. For instance, Patz et al. (61) believe that low-carbon can promote future health. Haines and Dora (62) suggest that low-carbon economic development could have many benefits for health, but they acknowledge that there was no broad consensus. Therefore, when analyzing the development of the low-carbon economy, we have considered its impact on health and explored it separately from the industrial, construction, and transportation sectors.

2.3. Influence of low-carbon economic development on GDP

Gross Domestic Product (GDP) refers to the total value of all final products and services produced by permanent residents of a country or region within a certain period (63). It is often considered to be an important indicator for measuring the economic situation of a country or region. Due to its significance, scholars have investigated factors that affect GDP, such as human capital structure (64), the stock of education capital and fixed assets (65), and innovation factors (66). In addition to these fundamental and strategic influencing factors, low-carbon economic development also has a significant impact on GDP, which many scholars have studied in depth.

However, some scholars who study the impact of low-carbon economic development on GDP calculate the impact of carbon emissions and energy consumption on GDP to get the indirect answer. For example, Li and Li (29) analyze the carbon emissions of the construction industry and found that reducing carbon dioxide emissions and improving energy efficiency are necessary to promote GDP growth. This answers the correlation between the development of a low-carbon economy and GDP in China's construction industry. In another study, a survey of CO_2 emissions in China's Yunnan Province found a significant impact between CO_2 and GDP, the study suggests that high-carbon sectors in the region would hinder the development of low-carbon economies and affect GDP growth in the future if the capital structure was not adjusted (67). A small number of scholars directly analyze the impact of low-carbon economic development on GDP by integrating a variety of data, such as carbon emissions and energy consumption. These researches usually bring more intuitive results. For instance, Zhang et al. (68) find that the implementation of an emission trading system (ETS) has a significant positive effect on GDP when a low-carbon economy develops. Sheng et al. (69) use the Tapio model to calculate the ratio of economic growth efficiency and carbon emission reduction efficiency to estimate low-carbon economic development and the study find that it has an obvious "U"-shaped relationship with the real per capita GDP.

Despite numerous scholars investigating the relationship between low-carbon economic development and GDP, the results show significant differences. From the studies of these scholars, there are evident differences between regions and sectors, such as Samour (70) focuses on the Turkish banking industry, Li and Li (29) study on China's construction sector, and Işık et al. (26) focuses on the top 10 cities with the highest carbon emissions in the United States. However, few scholars have explored the impact of low-carbon economic development on GDP from different sectors. Therefore, we take low-carbon economic development as a variable, starting from the perspective of multiple sectors, to explore the impact of low-carbon economic development on the GDP of China's industrial, construction, and transportation sectors, to obtain more connections and gaps between sectors.

3. Materials and methods

3.1. Data source and descriptive statistics

The study is conducted using a panel comprising 34 provinces in China, from 2005 and 2019. Owing to the missing date, Taiwan, Macao, Tibet, Hong Kong, Chongqing, and Ningxia are removed. Different provinces in China have heterogeneity in geographical location and economic development status. Therefore, the researchers could make a thorough analysis of the problem they are trying to explain due to their variability. Most of the data comes from the China Health Statistical Yearbook (33), China Statistical Yearbook (71), and the China Energy Statistical Yearbook (18). Among the variables, the data on the development of a low-carbon economy comes from Tapio decoupling model, that is, it is determined according to the ratio of to GDP the CO_2. This model mainly reflects the uncertain correlation between economic development, and carbon emission, and can be used to evaluate the development of a low-carbon economy (29, 72, 73). Blank data are padded by linear interpolation. Table 1 contains the definition of variables and other useful information.

Table 2 provides an overview of the descriptive statistics of the variables we used, covering all variables from multiple models, which can be grouped into four categories. The first category is the health status of residents, with a median of −0.155 and a difference of 7.764 between the maximum and minimum values. The second type is related to economic development, the median GDP of province-level

TABLE 1 Variable definition.

Variables	Definition	Period
CO_2	CO_2 emissions (kilogram)	2005–2019
GDP	GDP of each province (hundred million)	2005–2019
LE	Low-carbon economic development	2005–2019
H	Resident health problem (incidence of tuberculosis)	2005–2019
I	Industry	
C	Construction	
T	Transportation industry	

TABLE 2 Descriptive statistics.

Variable	ZH	ZGDP	ZCO_2	ZI_{CO2}	ZC_{CO2}	ZT_{CO2}	ZLE	ZI_{LE}	ZC_{LE}	ZT_{LE}
Median	−0.155	−0.278	−0.343	−0.274	−0.125	−0.149	−0.254	−0.218	−0.296	−0.130
Max	−1.517	−1.077	−1.357	−1.387	−0.497	−1.560	6.738	4.898	5.645	12.967
Min	6.247	4.925	4.023	3.459	19.065	4.109	−1.238	−1.315	−1.019	−1.077
Range	7.764	6.002	5.380	4.846	19.562	5.669	7.975	6.212	6.664	14.044

regions is −0.278, and the range is 6.002. The third category is carbon dioxide emissions. It mainly includes CO_2 emissions by industry. The largest median is for construction, and the largest range is also for construction. The last category is low-carbon economic development. In this category, transportation has the largest median, and the range from largest to smallest is transportation, construction, and industry.

3.2. Model formulation

Linear regression is the main empirical tool in economics, and numerous studies have reported the significance of linear regression models (74–77). Using regression models, this study confirms the connection between low-carbon economic development, health, the growth of the economy, and the emitting of carbon, and sectors. Sarwar et al. (19) confirm the positive dependence of carbon emissions on economic development. Spiteri and Brockdorff (78) propose correspondence between health status and economic development. Given the significant long-term impact of the economy on health, we exclude the influence of GDP according to the Frisch-Waugh-Lovell theorem when calculating the relationship between carbon emissions, low-carbon economic development and health (79, 80). Building on previous research, we try to introduce industry, construction, and transportation, and examine the connections and differences between variables in the different sectors. For example, how do carbon emissions affect health and economic development? Is a low-carbon economy essential for health and the GDP of different sectors? To answer these questions, we highlight two dependent variables with four models.

$$H_{it} = \beta_0 + \beta_1 CO_2 + \mu_{it} \tag{1}$$

$$H_{it} = \beta_0 + \beta_1 ZI_{CO_2} + \beta_2 ZC_{CO_2} + \beta_3 ZT_{CO_2} + \mu_{it} \tag{2}$$

$$H_{it} = \beta_0 + \beta_1 LE + \mu_{it} \tag{3}$$

$$H_{it} = \beta_0 + \beta_1 ZI_{LE} + \beta_2 ZC_{LE} + \beta_3 ZT_{LE} + \mu_{it} \tag{4}$$

$$GDP_{it} = \beta_0 + \beta_1 CO_2 + \mu_{it} \tag{5}$$

$$GDP_{it} = \beta_0 + \beta_1 ZI_{CO_2} + \beta_2 ZC_{CO_2} + \beta_3 ZT_{CO_2} + \mu_{it} \tag{6}$$

$$GDP_{it} = \beta_0 + \beta_1 LE + \mu_{it} \tag{7}$$

$$GDP_{it} = \beta_0 + \beta_1 ZI_{LE} + \beta_2 ZC_{LE} + \beta_3 ZT_{LE} + \mu_{it} \tag{8}$$

where β_1, β_2, and β_3 are the coefficients of variables, while μ_{it} is the error term and the distribution of it conforms to the normal distribution with a mean of zero. Also, i (i = 1, 2, 3..., N) represents the inquired provinces, while t (t = 1, 2, 3..., T) means the change in the time frame. At last, β_0 represents the constant. To help minimize heteroscedasticity and undulation in data, all of the variables in equations were standardized by zero-mean normalization.

4. Results

4.1. Unit root tests of augmented dickey-fuller test

The data used by the model is time series, to prevent the occurrence of spurious regression, we inspect the panel unit root of all variables using the ADF test, assuming a unit root in the null hypothesis. This is done before conducting the panel regression models. It is shown in Table 3, the results of the ADF test statistic for almost all sequence variables are less than the cut-off value of 5% significance level, the rejection of the null hypothesis of the ADF test indicates that the time series data is stationary. However, there is an exception, the variable Health is non-stationary, so we further perform second-order differential on the data, and after that, all variables become stationary.

4.2. Co-integration test

Cointegration tests help us determine whether the data exhibits a long-term stable relationship between a set of linear data. Consequently, we further examine the cointegration relationship of the linear regression model and perform a stationary analysis of the model residual sequence. As shown in Table 4, the residual sequence test results for models 1–6 are all less than the 5% cut-off value, so the residual sequences of these models are stable. Thus, the independent and dependent variables in this study are found to be co-integrated, indicating a long-term correlation between them.

4.3. Regression analysis

Table 5 reports the relationship between health and carbon emissions or low-carbon economic development with the low-carbon

TABLE 3 The values of the ADF test.

Variable		Differential order	*t*	*P*	AIC	Critical value			Results
						1%	5%	10%	
H	ZH	0	−1.31	0.625	498.024	−3.447	−2.869	−2.571	Non-stationary
		1	−5.905	0.000***	497.69	−3.447	−2.869	−2.571	Stationary
GDP	ZGDP	0	−3.911	0.002***	530.563	−3.447	−2.869	−2.571	Stationary
		1	−5.379	0.000***	543.866	−3.447	−2.869	−2.571	Stationary
CO_2	ZCO_2	0	−3.955	0.002***	384.852	−3.447	−2.869	−2.571	Stationary
		1	−5.217	0.000***	398.962	−3.447	−2.869	−2.571	Stationary
	ZI_{CO2}	0	−3.951	0.002***	357.786	−3.446	−2.868	−2.57	Stationary
		1	−20.776	0.000***	373.265	−3.446	−2.868	−2.57	Stationary
	ZC_{CO2}	0	−12.31	0.000***	1148.711	−3.446	−2.868	−2.57	Stationary
		1	−9.156	0.000***	1191.975	−3.447	−2.869	−2.571	Stationary
	ZT_{CO2}	0	−4.107	0.001***	557.938	−3.447	−2.869	−2.571	Stationary
		1	−5.969	0.000***	572.192	−3.447	−2.869	−2.571	Stationary
LE	ZLE	0	−3.612	0.006***	328.369	−3.447	−2.869	−2.571	Stationary
		1	−5.815	0.000***	338.418	−3.447	−2.869	−2.571	Stationary
	ZI_{LE}	0	−3.825	0.003***	393.318	−3.447	−2.869	−2.571	Stationary
		1	−5.659	0.000***	404.537	−3.447	−2.869	−2.571	Stationary
	ZC_{LE}	0	−4.864	0.000***	527.88	−3.446	−2.869	−2.571	Stationary
		1	−10.493	0.000***	546.66	−3.446	−2.869	−2.571	Stationary
	ZT_{LE}	0	−3.18	0.021**	1005.941	−3.447	−2.869	−2.571	Stationary
		1	−5.363	0.000***	998.181	−3.447	−2.869	−2.571	Stationary

*$p < 0.05$; **$p < 0.01$; ***$p < 0.01$.

TABLE 4 The residual sequence test results for models 1–6.

Variable	Differential order	*t*	*P*	AIC	Critical value			Results
					1%	5%	10%	
The residuals of model 1	0	−2.573	0.099*	430.985	−3.446	−2.868	−2.57	Stationary
	1	−6.608	0.000***	435.244	−3.447	−2.869	−2.571	Stationary
The residuals of model 2	0	−2.588	0.095*	437.674	−3.446	−2.868	−2.57	Stationary
	1	−5.861	0.000***	441.014	−3.447	−2.869	−2.571	Stationary
The residuals of model 3	0	−2.688	0.076*	425.04	−3.446	−2.868	−2.57	Stationary
	1	−16.65	0.000***	429.483	−3.446	−2.869	−2.57	Stationary
The residuals of model 4	0	−2.534	0.107	463.697	−3.446	−2.869	−2.57	Non-stationary
	1	−17.407	0.000***	467.751	−3.446	−2.869	−2.57	Stationary
The residuals of model 5	0	−2.698	0.074*	476.741	−3.447	−2.869	−2.571	Stationary
	1	−5.778	0.000***	482.033	−3.447	−2.869	−2.571	Stationary
The residuals of model 6	0	−3.888	0.002***	640.956	−3.447	−2.869	−2.571	Stationary
	1	−6.095	0.000***	653.993	−3.447	−2.869	−2.571	Stationary
The residuals of model 7	0	−4.44	0.000***	495.528	−3.447	−2.869	−2.571	Stationary
	1	−5.712	0.000***	513.914	−3.447	−2.869	−2.571	Stationary
The residuals of model 8	0	−5.654	0.000***	605.482	−3.446	−2.868	−2.57	Stationary
	1	−6.645	0.000***	627.913	−3.447	−2.869	−2.571	Stationary

*$p < 0.05$; **$p < 0.01$; ***$p < 0.01$.

economic development of industry, construction, and transportation, as shown in Equations 1–4. Table 6 reports the correlation in GDP, carbon emissions and low-carbon economic development of the three sectors, as shown in Equations 5–8.

TABLE 5 Model results with resident health problem as the dependent.

Dependent variable	Independent variable	Model 1	Model 2	Model 3	Model 4
H	CO_2	−0.082			
	I_{CO2}		0.070		
	C_{CO2}		−0.042		
	T_{CO2}		−0.061		
	LE			−0.168***	
	I_{LE}				−0.194***
	C_{LE}				−0.031
	T_{LE}				−0.104*

*$p<0.05$; **$p<0.01$; ***$p<0.01$.

TABLE 6 Model results with GDP as the dependent variable.

Dependent variable	Independent variable	Model 5	Model 6	Model 7	Model 8
GDP	CO_2	0.605***			
	I_{CO2}		0.323***		
	C_{CO2}		0.050*		
	T_{CO2}		0.619***		
	LE			0.533***	
	I_{LE}				0.582***
	C_{LE}				−0.052
	T_{LE}				0.183***

*$p<0.05$; **$p<0.01$; ***$p<0.01$.

For both Model 1 and Model 2, health is the dependent variable. The independent variable of Model 1 is overall carbon emissions, and our study finds that carbon emissions have no significant effect on overall health. The independent variables of Model 2 are carbon emissions from industry, construction, and transportation. Our results suggest that the health impact of carbon emissions in either sector is not significant, meaning that increased carbon emissions do not lead to more health problems directly.

Models 3 and 4 report the health impacts of low-carbon economic development, especially in the industry, construction and transportation sectors. As revealed by our research, the implementation of low-carbon measures in industry and transportation has a notable positive effect on health, while the construction sector is not. These two model results show that a strong low-carbon economy can help reduce health problem occurrence, especially in industry and transportation. Combining the results of models 3 and 4, we note the unusual nature of the industry. We found that the low-carbon progress of industry has a greater effect on reducing health problems than other sectors. This shows that industry has a greater impact on health than construction and transportation sectors. Industrial enterprises must pay more attention to the growth of the low-carbon economy.

For model 5, the findings from the linear regression analysis revealed a statistically significant positive correlation between emitting of carbon and regional GDP. Model 6 is an extension of Model 3 to further categorize carbon emissions into industrial, construction and transportation. It demonstrates that the carbon emissions of industry and transportation have a substantial beneficial impact on the regional GDP, while the emitting of carbon in the construction industry is not significant, which may be related to the unique features of the construction industry itself. The different impacts we observe on economic development from different sectors synthesize the results of some studies (43, 44, 81).

Models 7 and 8 illustrate a significant effect of low-carbon economic development on GDP. Derived from the outcomes of Model 7, low-carbon economic development has a considerable positive effect on regional GDP. Model 8 shows the impact of low-carbon economic development in industry, construction, and transport on GDP. We find that industry and transportation have a positive and significant influence, meantime, the impact of low-carbon economic progress in the construction industry is not significant, that is, from the overall point of view, the growth of the low-carbon economy will affect the collectivity economic progress, and by industry, the growth of the low-carbon economy in the construction industry has nothing to do with the overall economic development, and the industrial and transportation industry is consistent with the overall situation.

Combining the results of Models 6 and 8, we believe that both carbon emissions and low-carbon economic development can have a significant beneficial influence on regional economic development. For industry, low-carbon economic development owns a greater influence on the regional development of the economy than emitting carbon. Neither carbon emissions nor low-carbon economic development in the construction industry has a substantial beneficial effect on regional economic development. For the transportation industry, carbon emissions have a greater influence on regional economic development than low-carbon economic development. In summary, the reduction of emitting of carbon in industries will not bring about a reduction to every layer of the growth of the economy, although the effect of carbon emission reduction in other sectors on the economy is not as significant as that of industry, it will not have a negative impact.

5. Discussion and conclusion

5.1. Discussion

Low-carbon economic development is a crucial and effective approach for achieving sustainable economic growth and improving people's health. Our results indicate that carbon emissions have no direct impact on health but have a positive impact on GDP. However, low-carbon economic development has a positive effect on both health and GDP. Our findings align with some existing literature, showing that carbon emissions do not have a significant impact on health (38), but can be improving economic development (39) and that low-carbon economic development can simultaneously enhance human health and economic prosperity (61). Our research shows that the development of a low-carbon economy can bring multiple benefits, not only improving economic development but also promoting the residents' health.

The results of this study show that carbon emissions have no significant impact on health. Our conclusions are inconsistent with some previous studies suggesting that carbon emissions have significant negative effects on health (34, 82, 83). On the one hand, carbon emissions bring about a greenhouse effect, harming health by raising temperatures (38, 39). On the other hand, other harmful pollutants that accompany carbon emissions during the combustion of fossil fuels could harm health (35, 84). Goodman et al. (60) argues that health and carbon emissions are not independently correlated unless the environment is used as an intermediary. Our research directly links carbon emissions to residents' health and does not involve environmental impacts. Goodman's results have provided a good explanation for the differences between our results and some literature. Our findings also demonstrate that there is no direct relationship between carbon emissions and health in the industrial, construction, and transportation sectors. Guo et al. (41) investigate the health effects of the Chinese industry and find that particulate matter (PM) emissions accompanying carbon emissions are the main cause of health damage. Zhang et al. (85) also obtain similar results in their investigation of the relationship between energy, emissions, and health in the construction sector, finding that PM and air pollution are the main causes of health problems. In the transportation sector, the incomplete combustion of fossil fuels releases large amounts of carbon dioxide and brings various pollutants (86, 87), and the use of fossil fuels poses a significant health risk (88, 89). He and Qiu (40) propose in their investigation of the relationship between carbon emissions and health in the transportation sector in China that reducing the use of fossil fuels can reduce the pollution that accompanies carbon emissions and thereby reduce health problems. These studies support Goodman's (60) view that health and CO_2 emissions are not independently correlated, and further support our finding that there is no direct significant relationship between carbon emissions and health.

Our research shows that the development of a low-carbon economy has a positive and significant impact on health, this finding is supported by previous research (36). Broken down to specific sectors, the health impacts of low-carbon economic development are markedly different, it still shows positive and significant impacts in industry and transportation, but not significant in the construction sector. The reasons for this outcome may be linked to GDP and carbon emissions, which are commonly used to measure the progress of low-carbon economic development (29, 72, 73). When neither GDP nor carbon emissions have an impact on health, it is unlikely that the promotion of low-carbon economic development will significantly influence health. This finding is consistent with our results in the construction sector, which show that neither carbon emissions nor GDP have a significant effect on health. Further investigation into the underlying mechanism of this finding leads us to believe that the type and quantity of energy consumption remain crucial factors, and the coupling effect between GDP and carbon emissions should not be disregarded. When GDP and carbon emissions are weakly coupled, meaning that energy conservation and emission reduction efforts cannot achieve low-carbon economic development (73), there naturally is no significant impact on health.

It has been found that carbon emissions have a significant positive impact on GDP, which is supported by previous studies (21, 22). However, some studies have shown that carbon emissions do not necessarily promote GDP when the economy has reached a certain level of development (23–25). We believe that the reasons for the differences in research results may be related to the selected regions and countries, as they have significant differences in economic development level and industrial structure (26, 27). When comparing the impact of carbon emissions on GDP across different sectors, our results show that the impact of industry and transportation is significantly greater than that of construction. Previous studies have shown an increasing dependence of the transportation sector development on CO_2 emissions, and carbon emissions play a significant role in promoting economic development (90), while Li and Li (29) propose that carbon emissions have less effect on economic development in the construction sector. We think that the reasons for the differences between sectors may be related to population, energy structure, and energy efficiency (29, 90). In addition, the level of industry development may also be the main reason for the difference, and scholars usually use economic and social indicators for comprehensive measurement (91–93). Some studies have shown economic development and carbon emissions are linked through the Environmental Kuznets Curve (EKC)[1] mechanism (94–96). Currently, China's carbon emissions are increasing with economic growth, within the climbing stage of the mechanism's inverted U-shaped curve. Our findings on the impact of carbon emissions on economic development support this view. The situation in the industrial and transportation sectors should be closer to the initial stage of EKC, while the construction industry should be closer to the inflection point.

The results demonstrate that low-carbon economic development has a significant, positive impact on GDP, as documented in previous literature (67, 68). Promoting economic growth is an important prerequisite for developing a low-carbon economy, as low-carbon economic development can significantly increase a country or region's

1 Environmental Kuznets Curve (EKC) proposed by Panayotou in 1993, which is an inverted U-shape curve reflect the relationship between environmental quality and per capita income.

gross domestic product. Du et al. (97) discover a positive correlation between the level of economic development in most provinces in China and carbon emissions. However, some cities are experiencing decoupling. Decoupling implies that economic development no longer leads to increased carbon emissions, and efforts to reduce carbon emissions do not hinder economic development, such as Guangdong and Jiangsu (73, 98), which have achieved higher levels of economic development and lower carbon emissions through improved energy efficiency and the development of information technology (73, 99). These findings are consistent with our findings. In our survey across various sectors, we observed that the development of a low-carbon economy in the industrial and transportation sectors has a significant positive impact on GDP. However, we did not find a significant impact of low-carbon development in the construction sector on GDP. In the industrial sector, there is a weaker decoupling relationship between carbon emissions and GDP (100, 101), indicating that carbon emissions are growing at a slightly slower rate than GDP. Similar results were found in the transportation sector (102, 103). However, in the construction sector, Zhang et al. (104) find diverse decoupling relationships between carbon emissions and economic development, with most provinces exhibiting either strong or weak decoupling and evident spatial heterogeneity. Consequently, low-carbon economic development in the construction industry does not significantly impact GDP. Further analysis suggests that the level of industrial economic development may be a contributing factor. Additionally, the source of carbon emissions could also explain the variations between industries. While carbon emissions in the industrial and transportation sectors mainly result from the use of fossil fuels, the construction industry's carbon emissions come not only from fossil fuel consumption but also from activities involving concrete and dump trucks (105, 106).

5.2. Conclusion

This study uses regression models to discover the relationship between health, GDP, and low-carbon economic development. To this end, we used data from 28 province-level regions in China between 2005 and 2019 to further categorize data on low-carbon economic development, carbon emissions, and regional GDP according to industry, construction, and transportation, delved into it to obtain cross-industry findings. The ADF root test and co-integration test were used to verify the model's validity and the long-term stable relationship between the data. The model results report the positive significant impact of low-carbon economic development on health and GDP. However, when it comes to specific sectors, these impacts may not be significant. We note that the influence of low-carbon economic development on health and GDP varies significantly between different sectors.

This study has important theoretical implications. First, we survey the development of low-carbon economies across the whole and by sectors, and most previous studies have ignored comparisons between sectors and rarely covered differences between sectors and the whole. Comparing sectors can provide valuable insights into data analysis and help us understand relative-level relationships between phenomena. Furthermore, comparing sectors to the overall economy allows us to examine the relationship between the whole and its parts, thereby uncovering differences and contradictions. These sector comparisons enable us to identify bottlenecks and shortcomings in low-carbon economic development and devise targeted solutions to address them. Secondly, by discussing the impact of carbon emissions and the development of a low-carbon economy on health, it is clear that the development of a low-carbon economy can contribute to the improvement of health issues. By reducing reliance on fossil energy and enhancing energy efficiency, low-carbon economic development can effectively reduce carbon emissions, improve the national economy and promote the health of residents. Conducting horizontal comparisons across sectors allows us to identify sectors that have a significant impact on human health, enabling us to address and mitigate potential health hazards. Taking sectors that can promote human health, such as industry and transportation, as a reference, guiding improve residents' health, which has not been covered in most previous studies focusing on region (47) or single (48) sectors. Previous studies on the health or economic impacts of low-carbon economic development often did not indicate their direct impact but used carbon emissions as an intermediate means to reach conclusions (67). This study uses regression models to reveal the direct impact of low-carbon economic development on health or the economy, which helps to reach clearer conclusions. In addition, the study expands the understanding of the health or economic impacts of low-carbon economic development in different industries, complementing previous research results based on regions (26, 29) or single sectors (70).

This study has important practical implications and serves as a reference for governments and enterprises. Our research findings highlight the critical role of carbon emissions in economic development. We have demonstrated that low-carbon economic development is a key pathway toward achieving sustainable development. The Chinese government should prioritize low-carbon and sustainable economic development, continue implementing low-carbon measures, and accelerate the transformation and upgrading of the industrial structure. The results of industrial data comparison point out that in the industrial and transportation sectors, carbon emissions and low-carbon economic development both play a positive role in GDP. Therefore, in the industrial sector, the government should gradually increase investment in science and technology, accelerate industrial upgrading, reduce energy consumption, improve energy efficiency, and develop zero-carbon factories. In the transportation sector, the government should optimize the transportation structure, encourage the use of new energy vehicles, strengthen people's environmental education, and improve awareness of low-carbon and green travel. For the construction sector, since the development of a low-carbon economy does not have a significant role in GDP at present, the Chinese government should make appropriate adjustments based on good practices in the industrial and transportation sectors and propose targeted low-carbon measures for construction consumables and large loading vehicles. Our findings also show that low-carbon economic development in industry and transportation can have a positive effect on health. We suggest that the Chinese government should focus on sectors where industry and transportation play a significant role in improving health, advocate for the reduction of fossil fuel usage, increase investment in new energy sectors, proposes incentive policies for energy conservation and emission reduction, encourages residents to travel in a green and healthy manner, and ultimately aim to improve resident health.

Furthermore, this study will help industrial, construction, and transportation enterprises understand the differences between low-carbon economic development sectors, enhance their awareness of low-carbon development, and provide a clear reference for their carbon emission reduction goals. Enterprises can establish energy monitoring and control centers to improve the sustainable growth of energy conservation and emission reduction with automation and informatization. They can also do a good job in the transformation and application of new energy technologies, and achieve low-carbon economic development through effective supervision and the use of infrastructure.

There are several limitations to this study. Firstly, the data used in this study are limited to China. Although China is a major carbon emitter, the results cannot be generalized to other countries and regions due to the differences in their levels of economic development. Future research on low-carbon economic development should survey more representative countries or even the world, and determine the differences in the impact of low-carbon economic development on health and GDP in countries or regions with different levels of economic development. Secondly, when investigating the impact of low-carbon economic development on GDP in different sectors, this study only focuses on industry, construction, and transportation, as they are important sectors that affect the country's economy and carbon emissions (107). Future research could investigate the development of low-carbon economies in more specific sectors, such as food manufacturing and textiles, which are also important concerns for national sustainable development. Additionally, further investigation is needed to explore the specific impact of carbon emissions and low-carbon economic development on health across different sectors. This is crucial as health is an essential requirement for promoting comprehensive human development and serves as a fundamental condition for economic and social progress (108). Future research should prioritize the investigation of this aspect, expanding the scope to include more regions and countries, as well as examining specific sectors in more detail, such as heavy industry and light industry.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SB: conceptualization, methodology, software, investigation, writing—original draft, and funding acquisition. JZ: investigation, data curation, and writing—original draft. MY: conceptualization, resources, supervision, writing—review and editing. ZY: resources and supervision. YC: software and validation. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1181623/full#supplementary-material

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